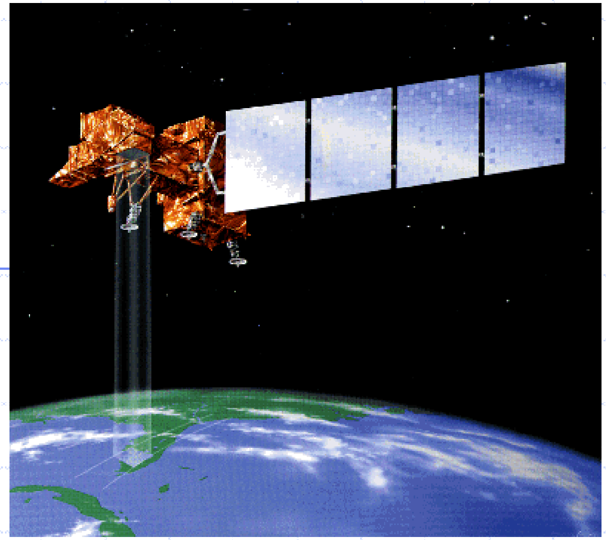
METRIC: High Resolution Satellite Quantification of Evapotranspiration



University of Idaho, Kimberly, Idaho

Part One – Introduction

University of Idaho · USDA ARS · USGS science for a changing world · Raytheon · NASA · IDWR

Co-developers and collaborators

- R.Allen, M.Tasumi, R.Trezza, C.Robison, J.Kjaersgaard, UI
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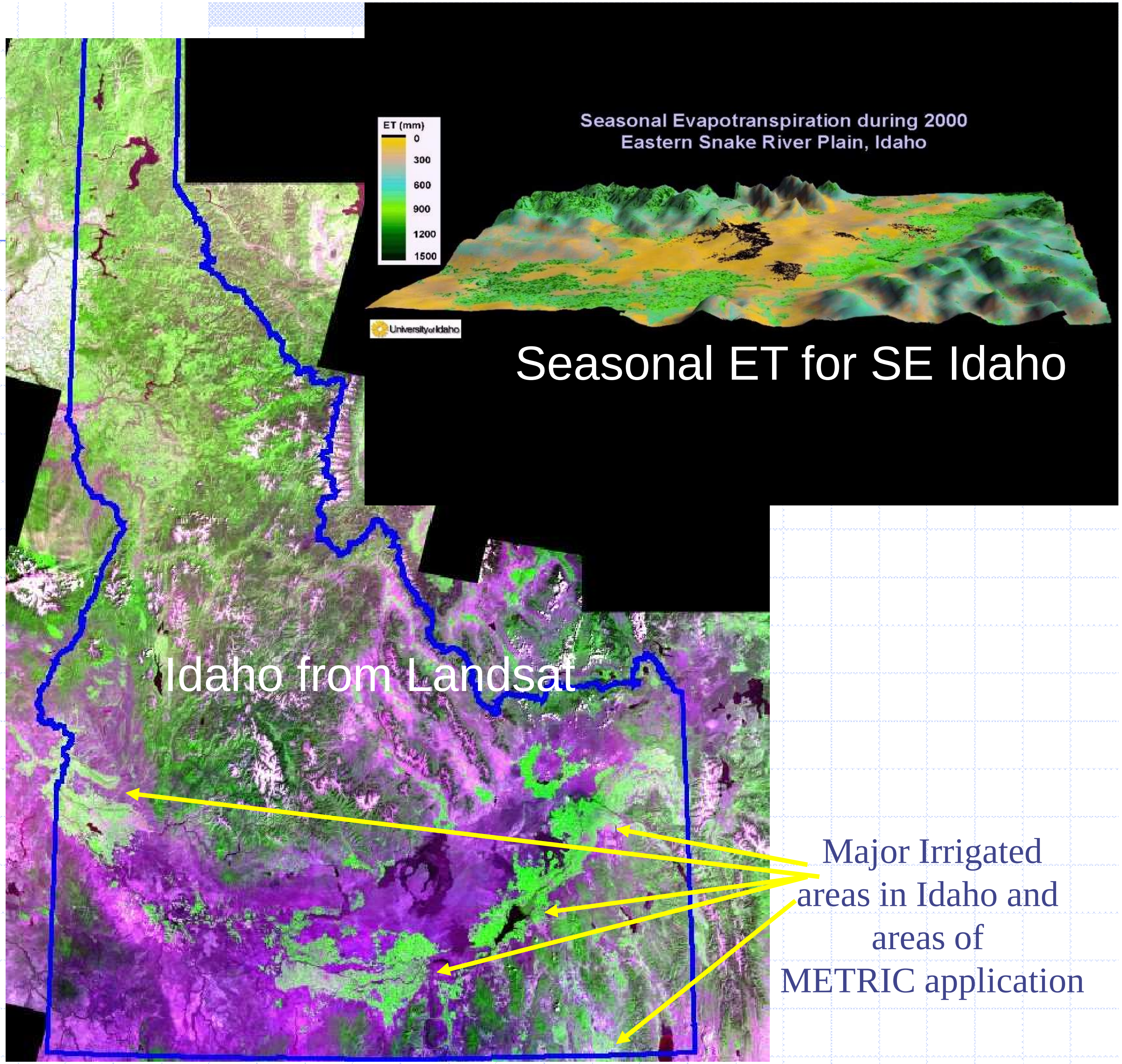
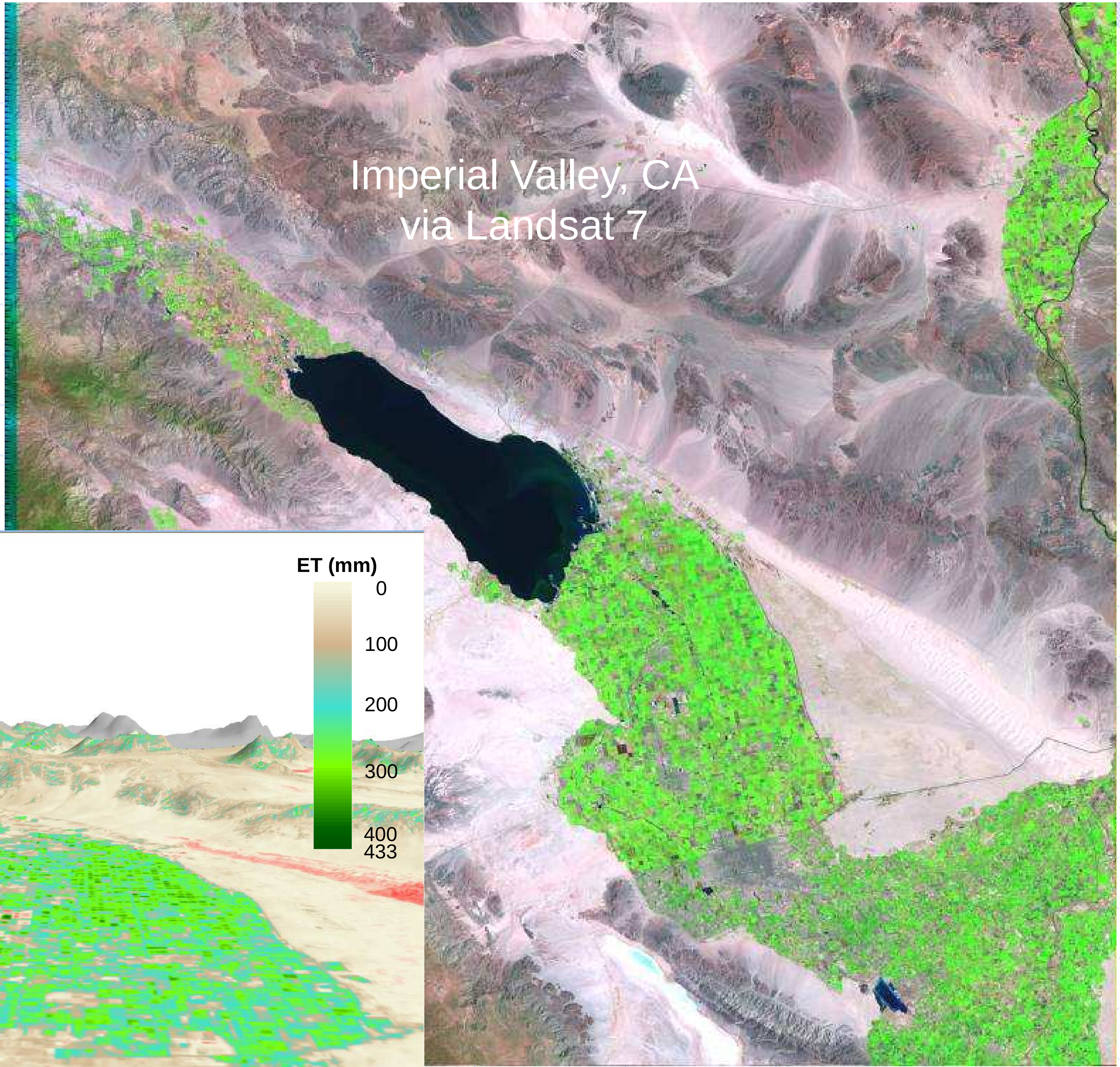
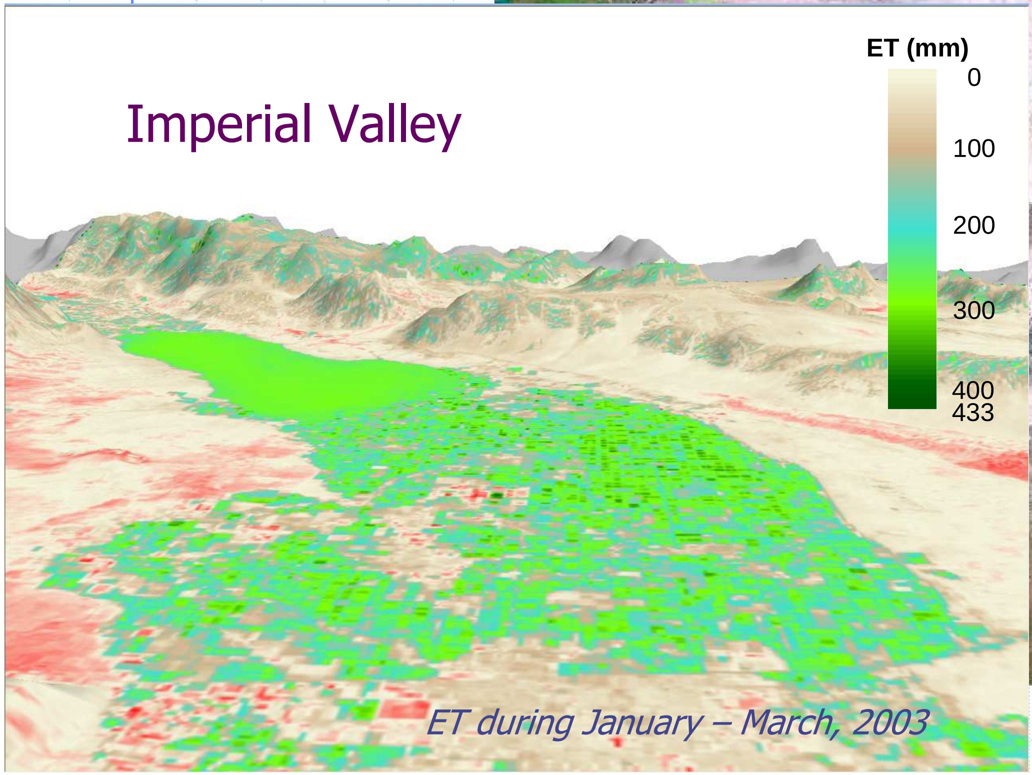
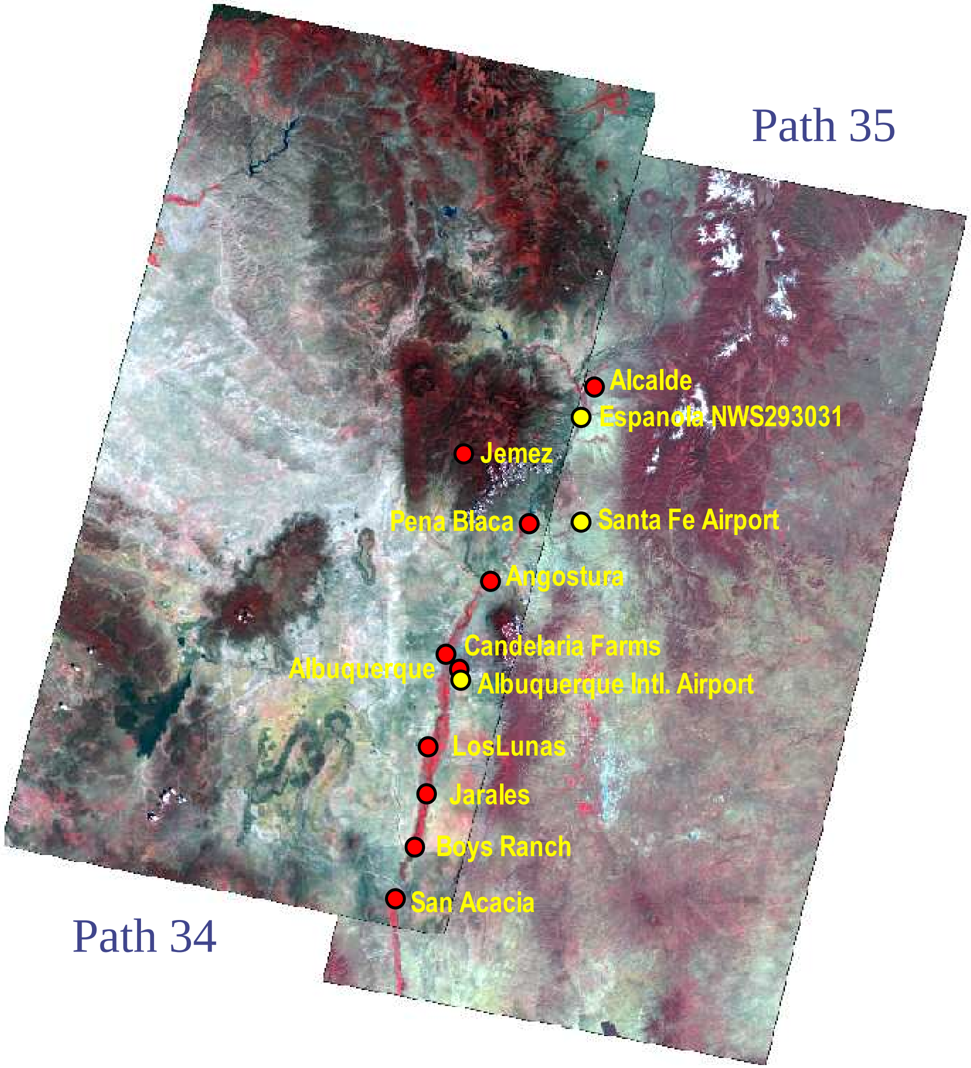
- W.Bastiaanssen, Waterwatch; J.Wright, USDA-ARS
- J.Hendrickx, NM Tech
- Ayse Irmak, Univ. Nebraska
- Justin Huntington, Desert Research Institute
- Riverside Technology, Inc.

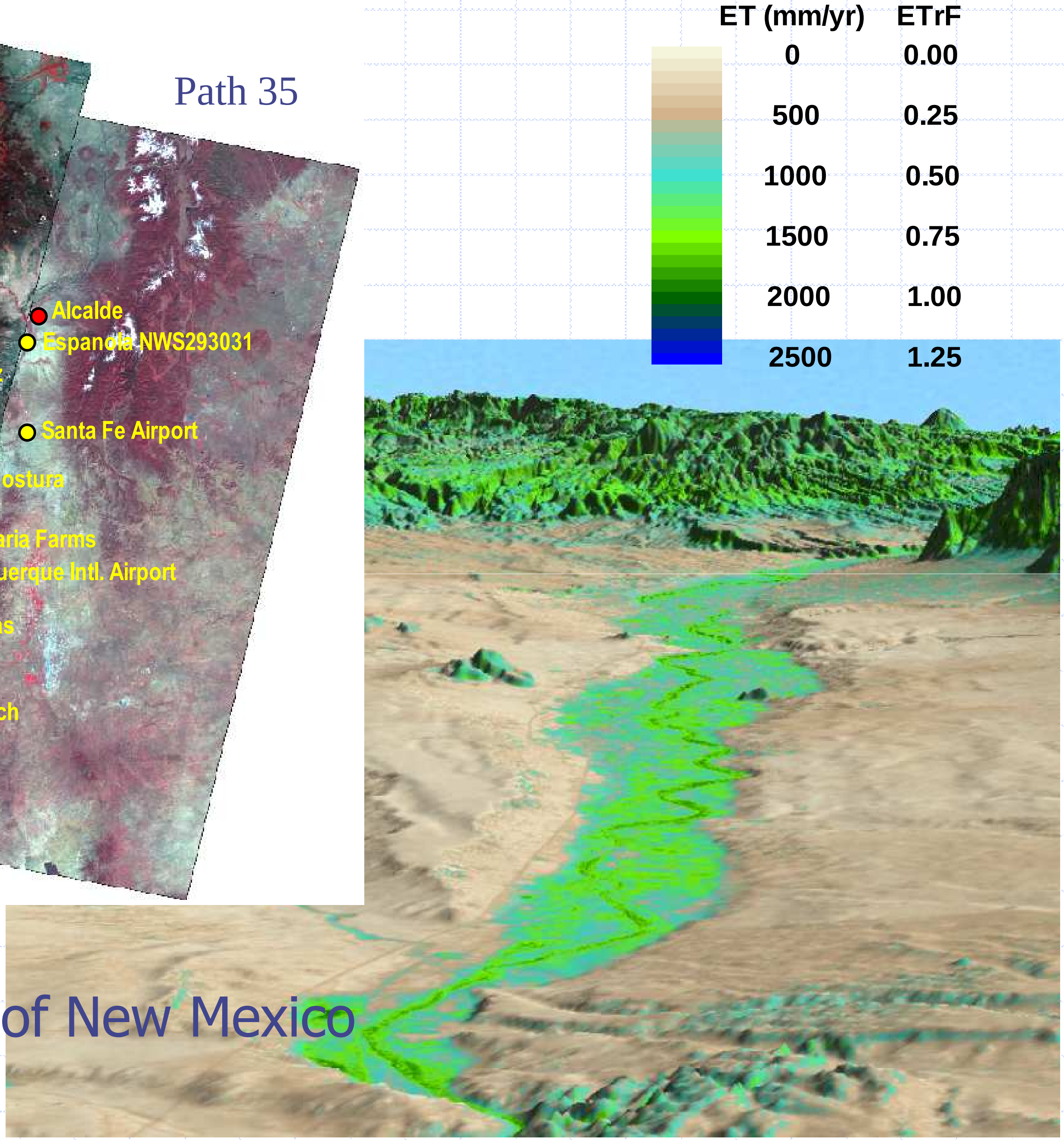
A few applications that helped to shape METRIC




Imperial Valley, CA
via Landsat 7

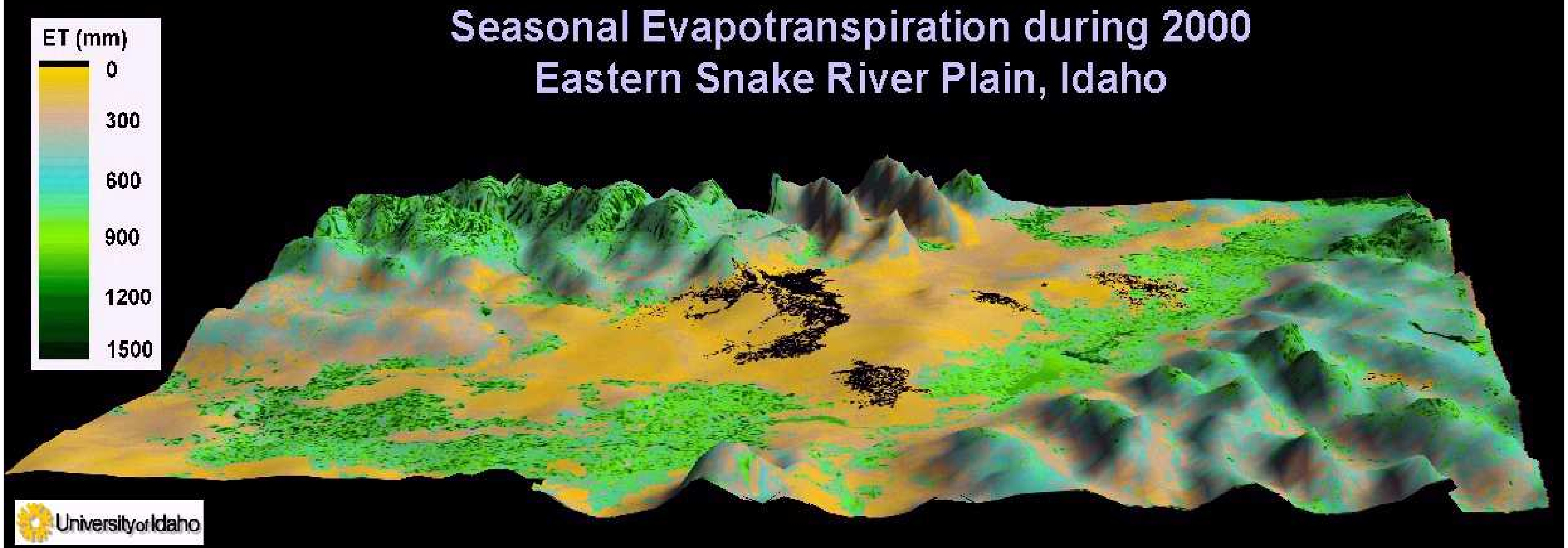

Imperial Valley
ET (mm)
0
100
200
300
400
433
ET during January – March, 2003





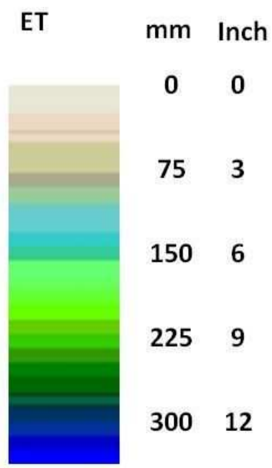
Middle Rio Grande of New Mexico

Product of METRIC^{tm} for Southeastern Idaho



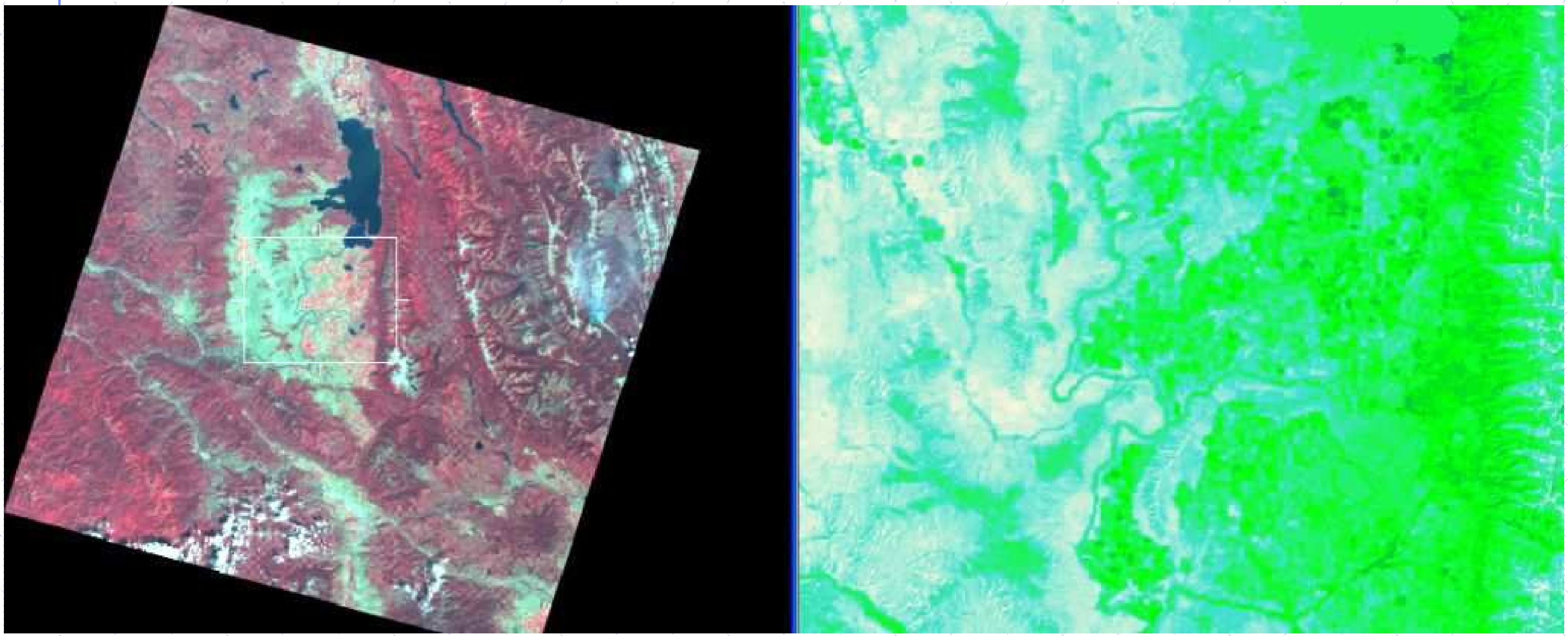
200 miles

3 million acres with 30 m resolution

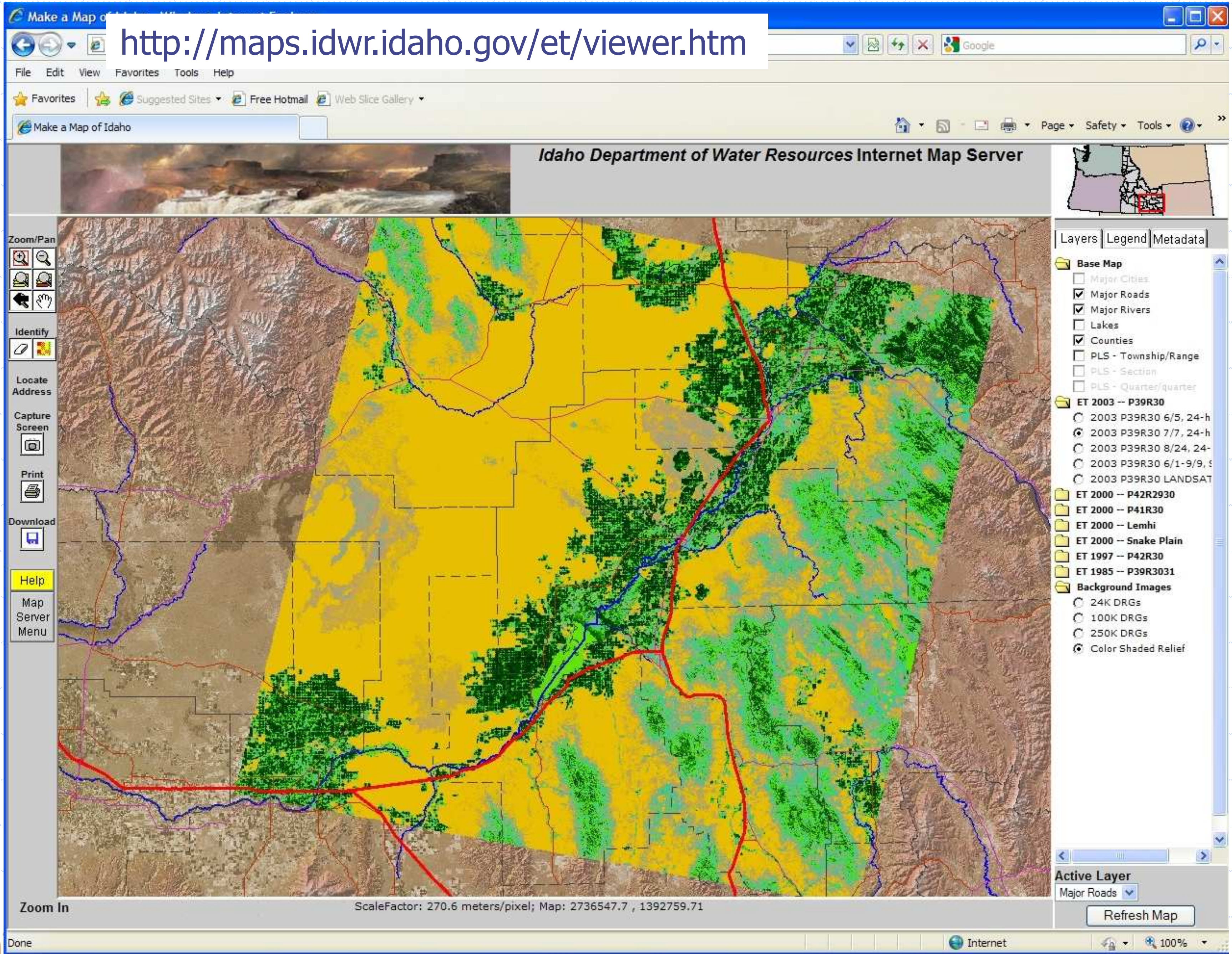


Product- Monthly ET

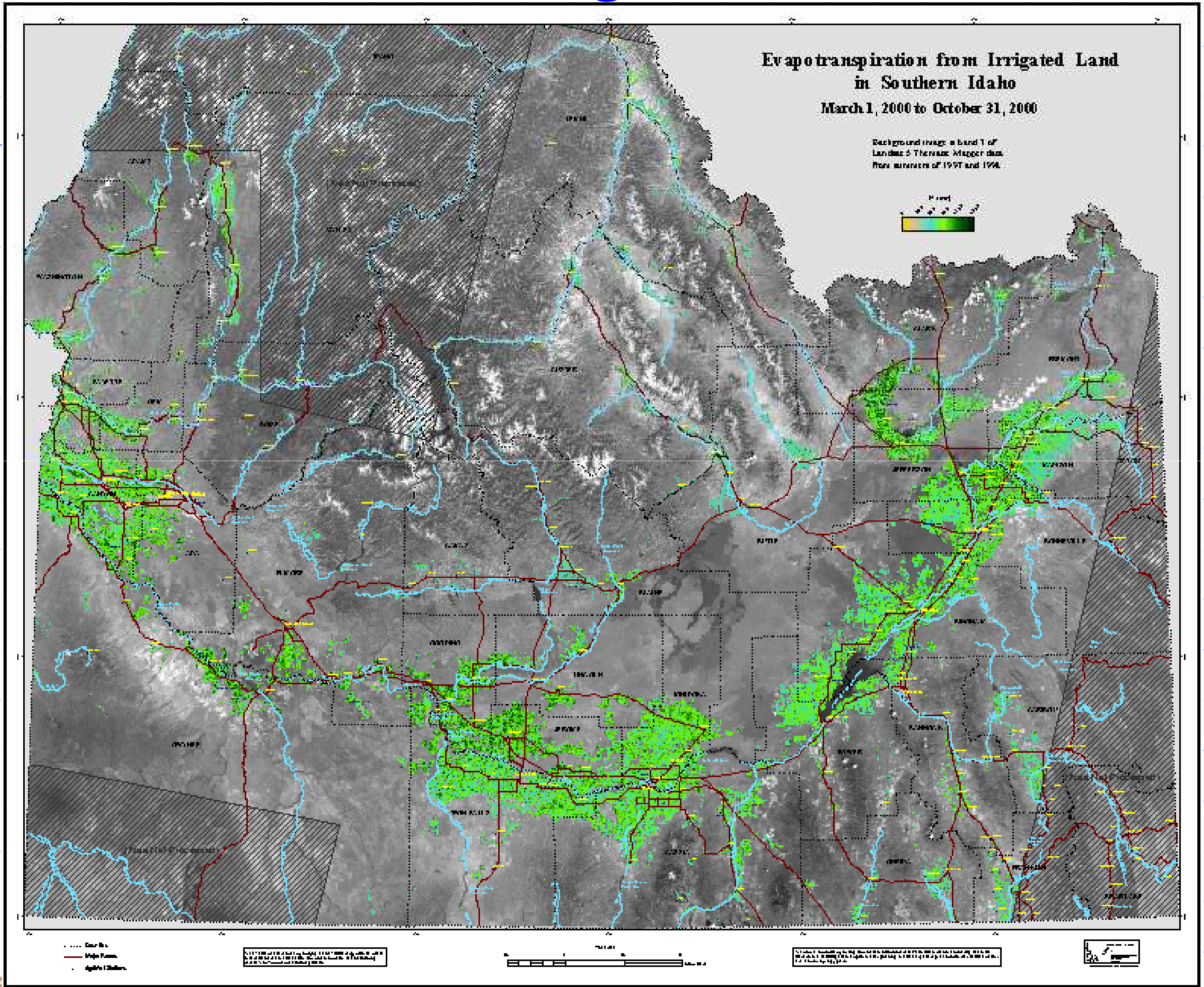
Summed ET for the Mission Valley, MT for during July, 2008



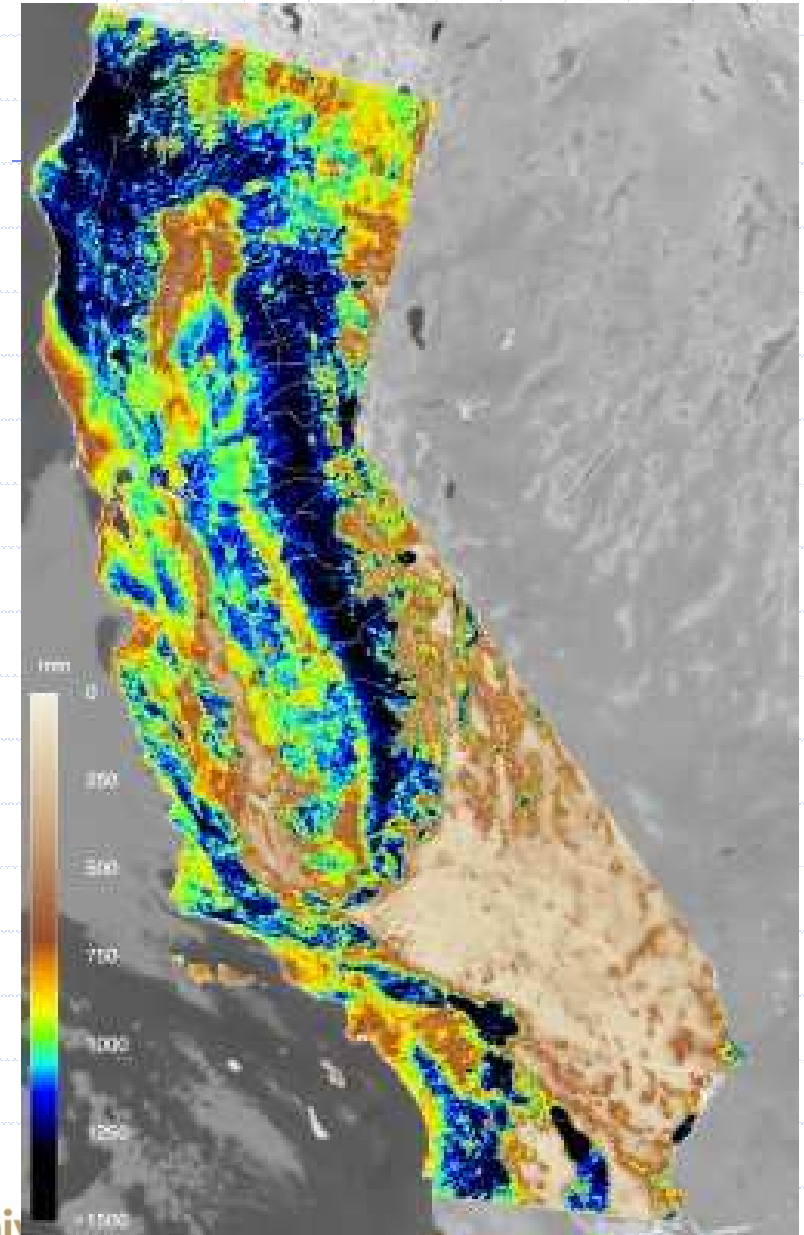
http://maps.idwr.idaho.gov/et/viewer.htm



Seasonal ET from Irrigated Areas for S. Idaho



Annual ET for all of California



Created by SEBAL-North America for 2002 using MODIS satellite imagery (resolution = 1 km)

http://www.sebal.us

Background on the ET mapping procedure

Evapotranspiration "mapping" with SEBAL and METRIC^{tm}

- Surface Energy Balance Algorithm for Land

  Dr. Wim Bastiaanssen,
  WaterWatch, *The Netherlands*
  – *beginning in 1990*
  – *SEBAL is commercially applied in the U.S.A. by SEBAL-North America*

- Mapping EvapoTranspiration with high Resolution and Internalized Calibration

  Allen, Tasumi,
  University of Idaho, *Kimberly*
  – beginning in 2000
  – rooted in SEBAL^{2000}

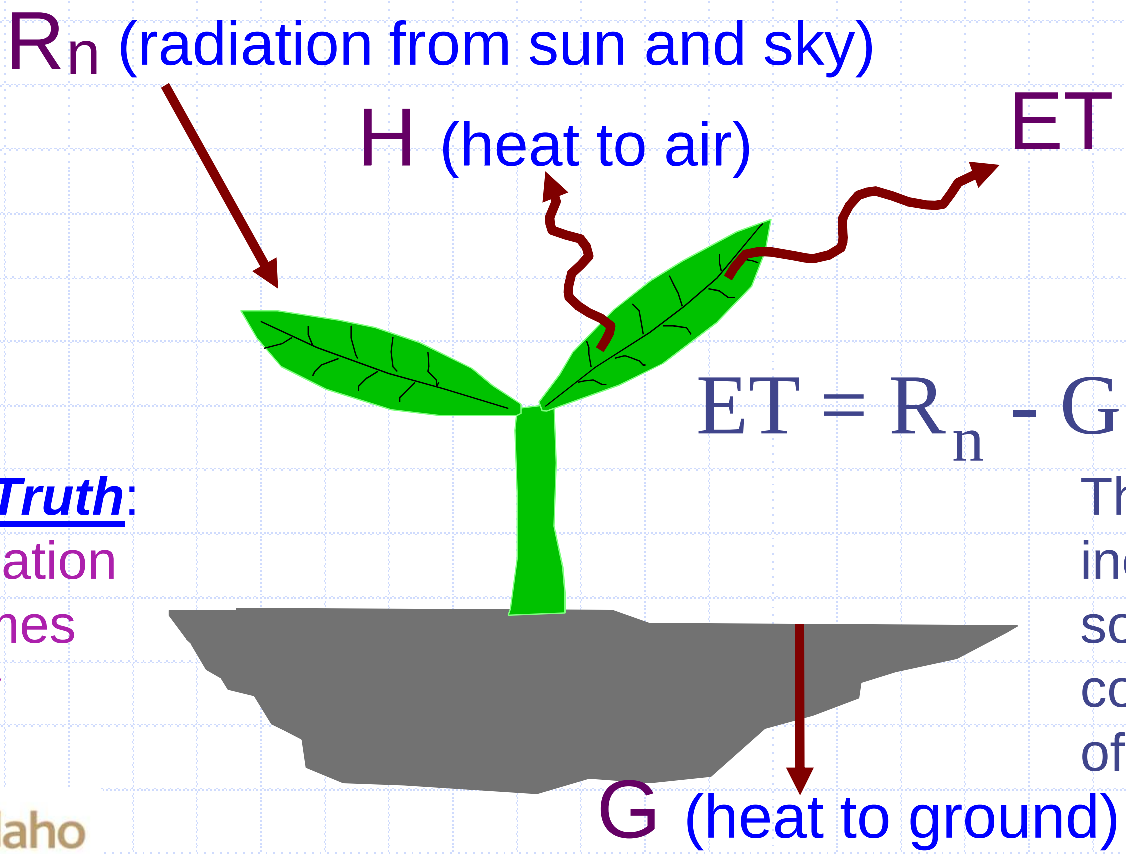
METRIC^{tm} is energy-balance-based ET mapping tied down and partly calibrated using ground-based reference ET (from weather data)

METRIC^{tm} works well in advective conditions of the western U.S.

Energy balance gives us "actual" ET

Surface Energy Balance:

- ET is calculated as a "residual" of the energy balance



$$ET = R_n - G - H$$

Basic Truth:
Evaporation consumes Energy

The energy balance includes all major sources (R_n) and consumers (ET, G, H) of energy

Via the Energy Balance we can "see" reduction in ET caused by

- soil water shortage (stress)
- plant density
  - low plant population or size
  - planting skips
  - wide row spacings
- soil salinity
- fertility deficiencies
- disease
- insect pressures
- weeds
- senescence
- tillage/traffic
- hail/frost

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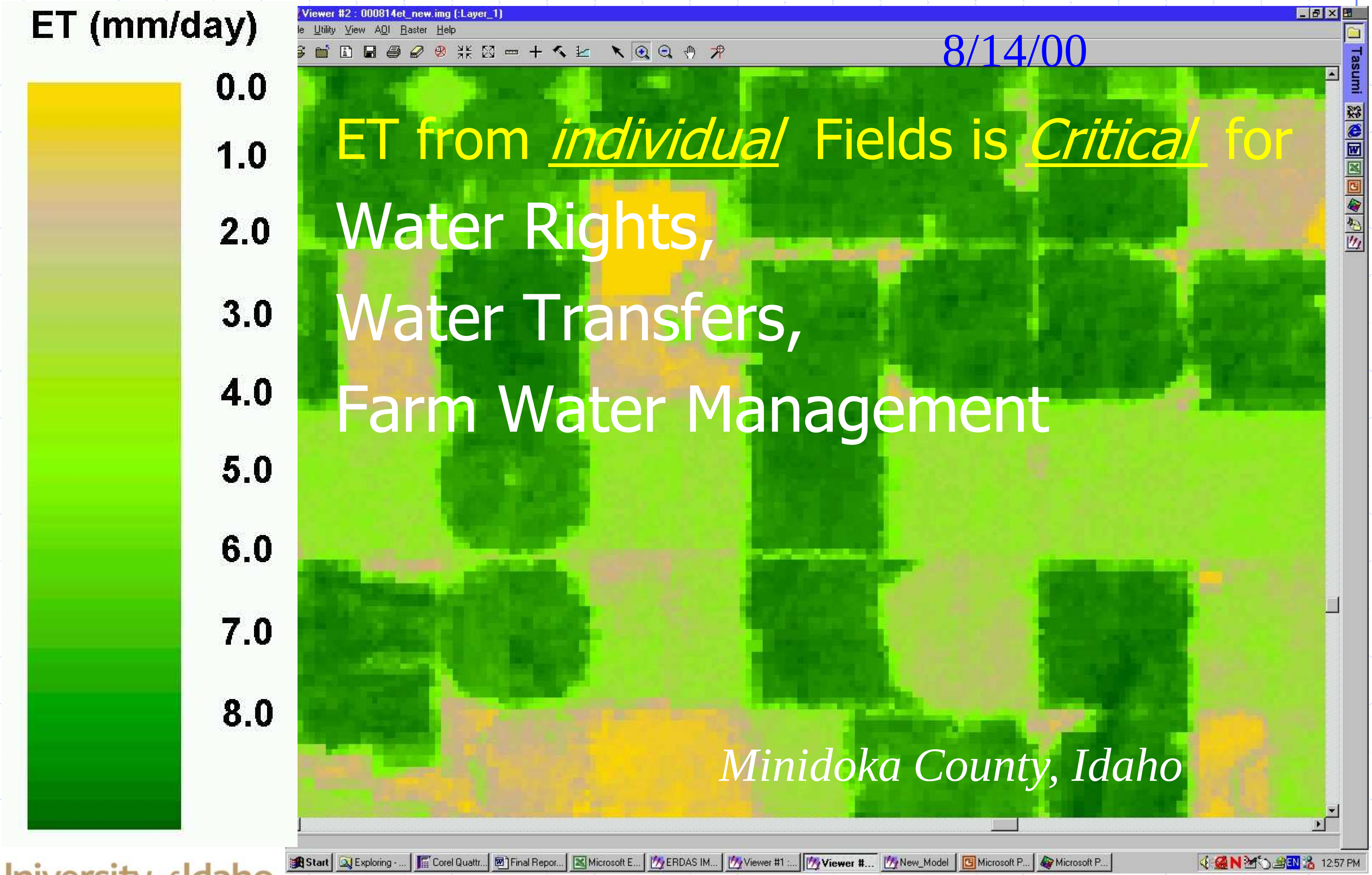
Why use High Resolution Imagery?



ET from *individual* Fields is *Critical* for

Water Rights,

Water Transfers,

Farm Water Management

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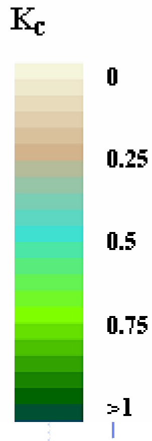
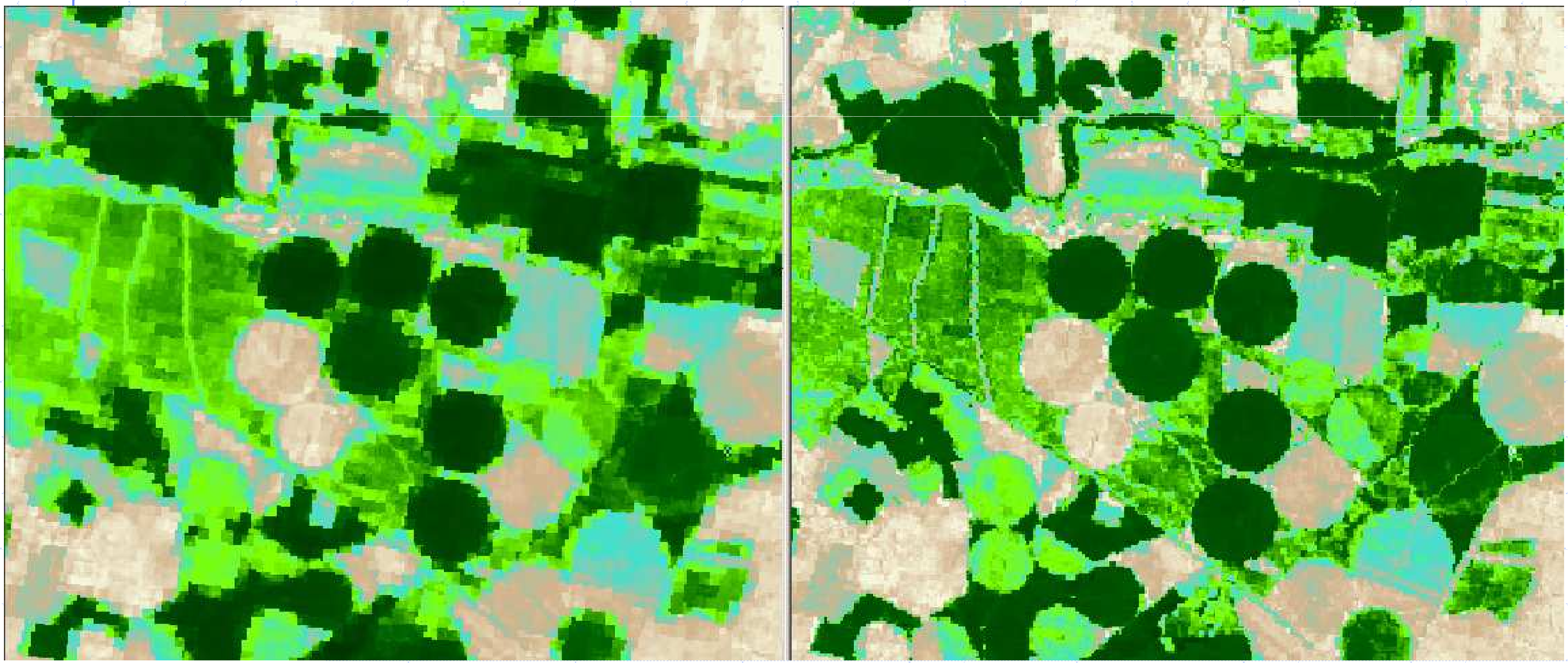
Sharpening of Thermal Band of Landsat 5 from 120 m to 30 m using NDVI

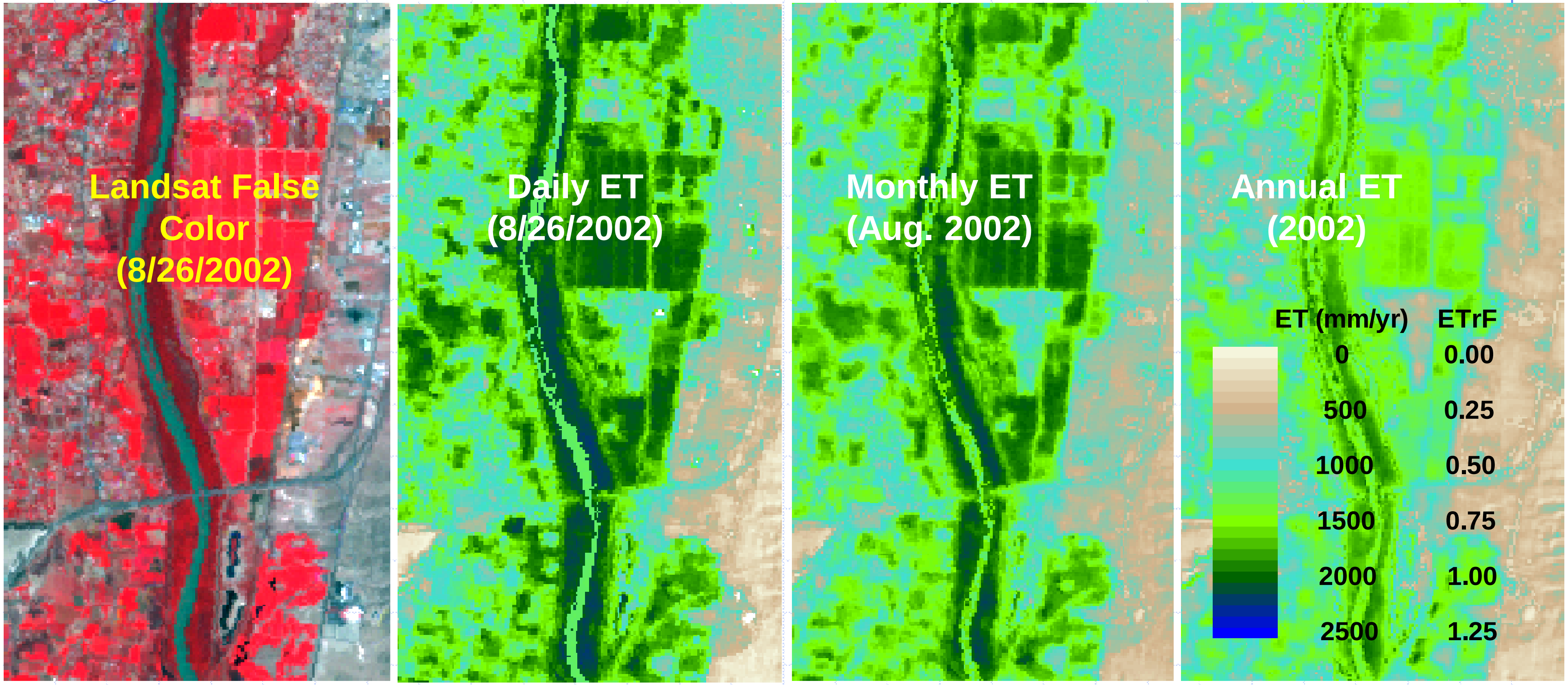


Landsat 5 -- Albacete, Spain, 07/15/2003

ET ratio before sharpening | ET ratio after sharpening

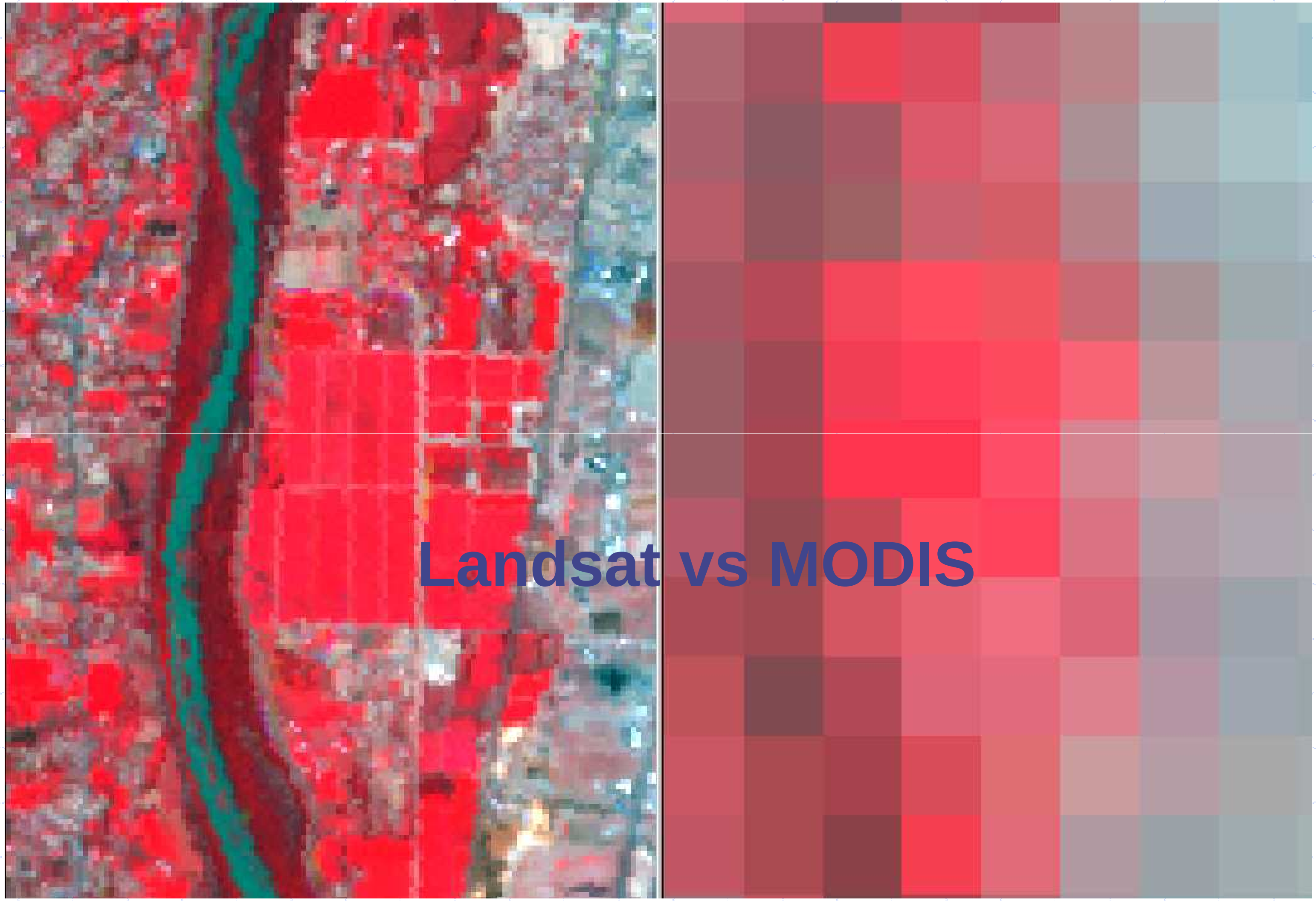


Why use High Resolution Imagery?



Riparian vegetation and small fields along the Middle Rio Grande, New Mexico

Why use High Resolution Imagery?



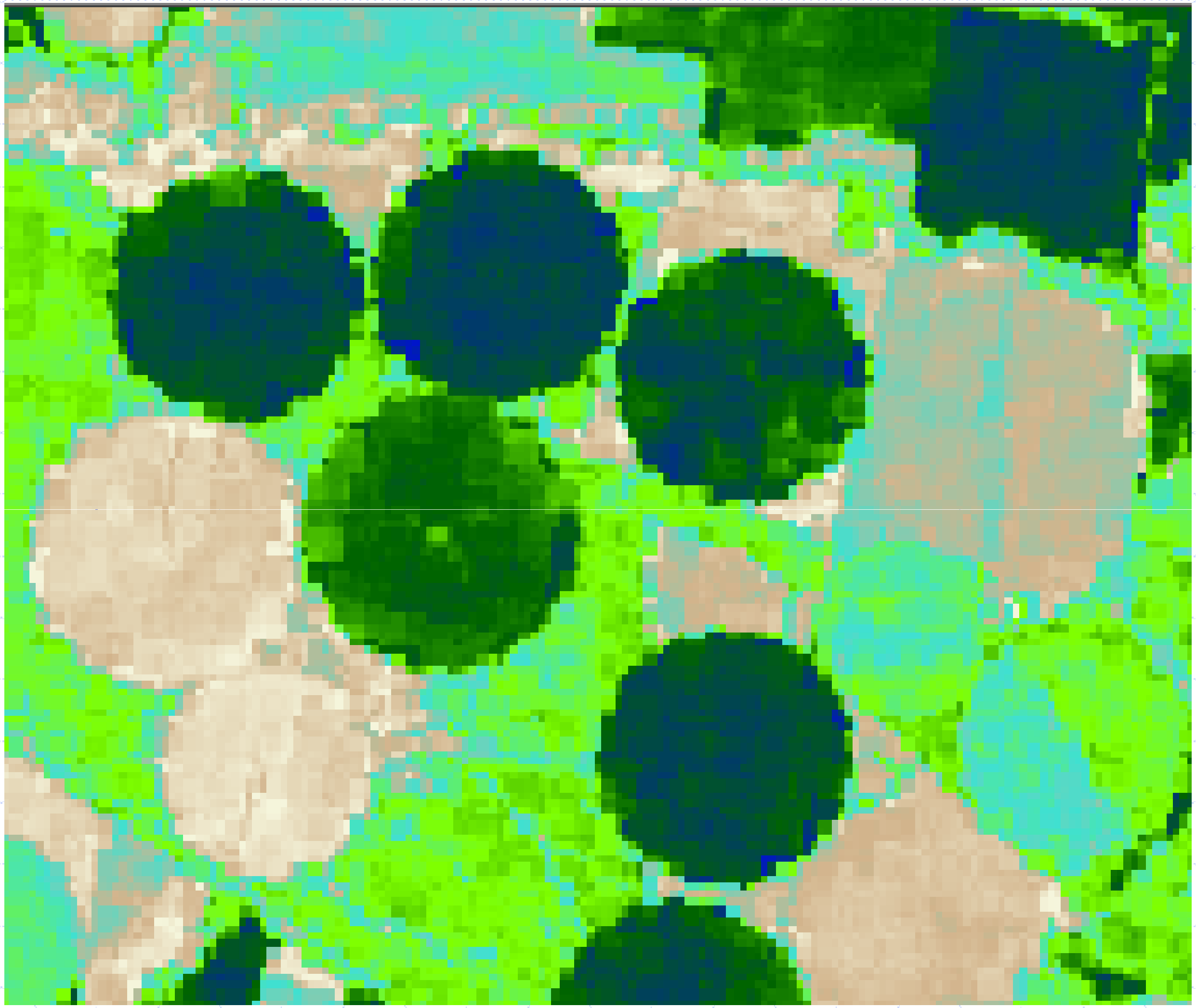
Landsat False Color (MRG)
8/26/2002 10:33am

MODIS False Color (MRG)
8/26/2002 11:02am

Need for ET Maps in Idaho

- Quantify Net Depletion from Ground-water Pumping *(unmeasured)*
- Compare actual ET with Water Right
- Calculate Natural and Irrigation-Induced Recharge to Aquifers
  (via water balance to calibrate MODFLOW)
- Determine "Actual" ET for Developing better Crop Coefficient Curves

Uses of ET maps



ET from Landsat 5 with thermal sharpened to 30 m

ET_rF

0.00
0.3
0.6
0.9
1.2
1.4

$(ET_rF = ET_{act} / ET_{ref})$

ET from <u>individual fields</u> is <u>essential</u> for: Water Rights, Water Transfers, Farm Water Management, verification of pumping records

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--Barrax, Spain, Allen and Trezza, 2004

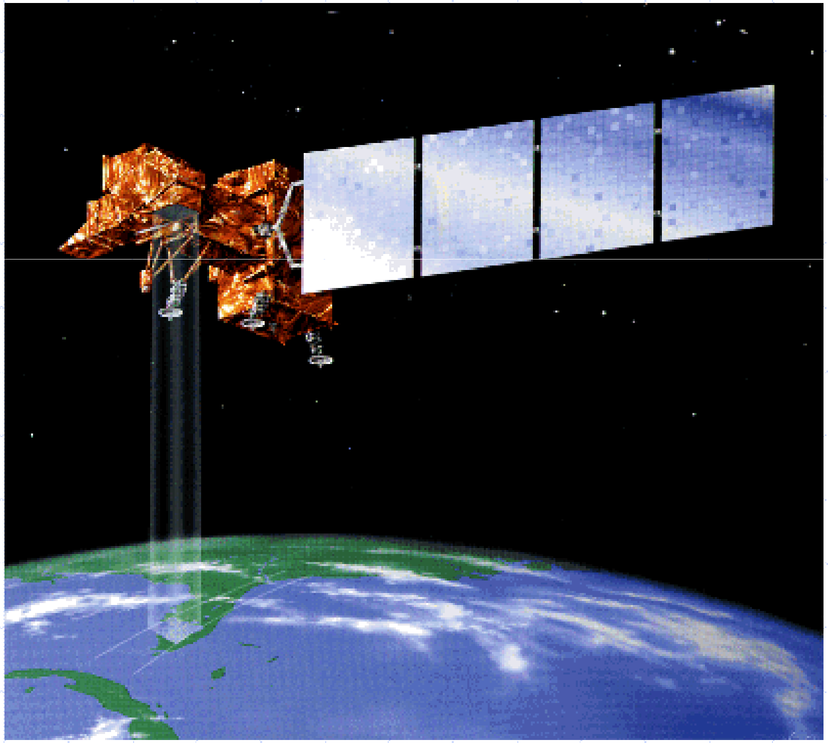
Other Applications

- ET from natural systems
  - wetlands
  - rangeland
  - forests/mountainous areas
  - hazardous waste sites
- ET from cities
  - changes in ET as land use changes

Definition of Remote Sensing:

The art and science of acquiring information using a non-contact device

Landsat 5



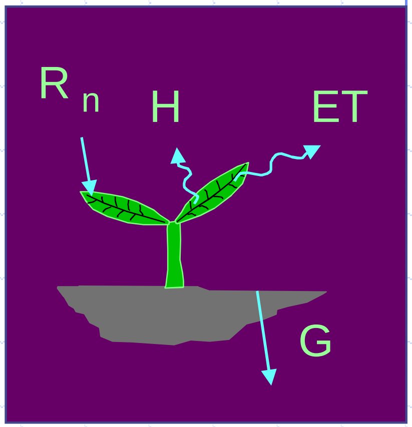
Landsat 7

Why Satellites?

- Typical method for ET:
  - **weather data** are gathered from fixed points -- assumed to extrapolate over large areas
  - **"crop coefficients"** assume ***"well-watered"*** situation ***(impacts of stress are difficult to quantify)***
- Satellite imagery:
  - **energy balance** is applied at *each "pixel"* to map spatial variation
  - areas where **water shortage reduces ET** are identified
  - **little or no ground data** are required
  - valid for **natural vegetation**

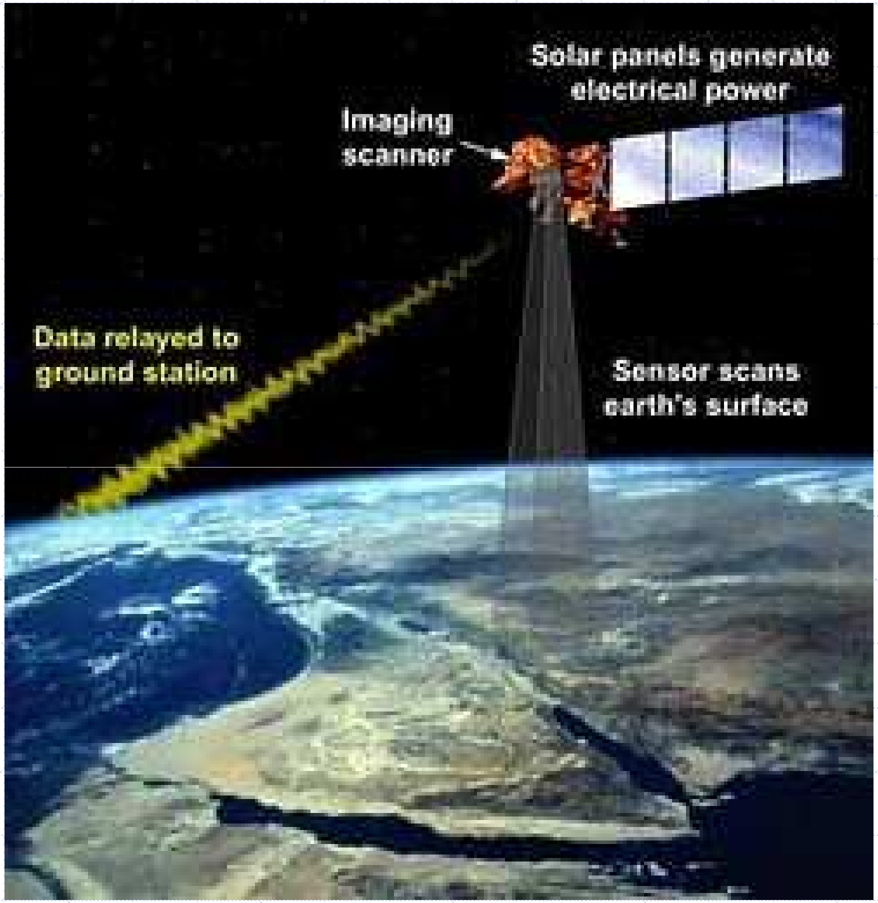
Components of the Energy Balance and those retreived via satellite

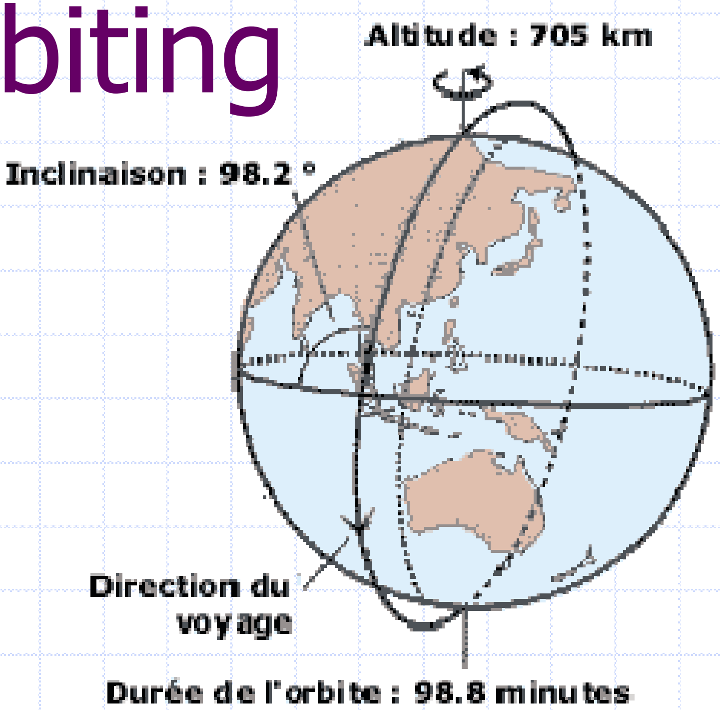
- **Net Radiation** (R_n) = function of:
  - date and time
  - _reflectance_ (brightness) of surface
  - _surface temperature_
  - humidity (minor effect)
- **Heat to Air** (H) = function of:
  - _surface temperature_
  - wind speed
  - _vegetation_ type and "roughness"
  - surface to air temperature difference:
    - H at the "cold" pixel = $R_n - G - ET_{reference}$
    - H at the "hot" pixel = $R_n - G - 0$
- **Heat to Ground** (G) = function of:
  - _amount of vegetation_
  - _Net radiation_
  - _surface temperature, reflectance_



underlined terms are measurable by satellite

Landsat – Polar Orbiting





A new image each 16 days for a specific location

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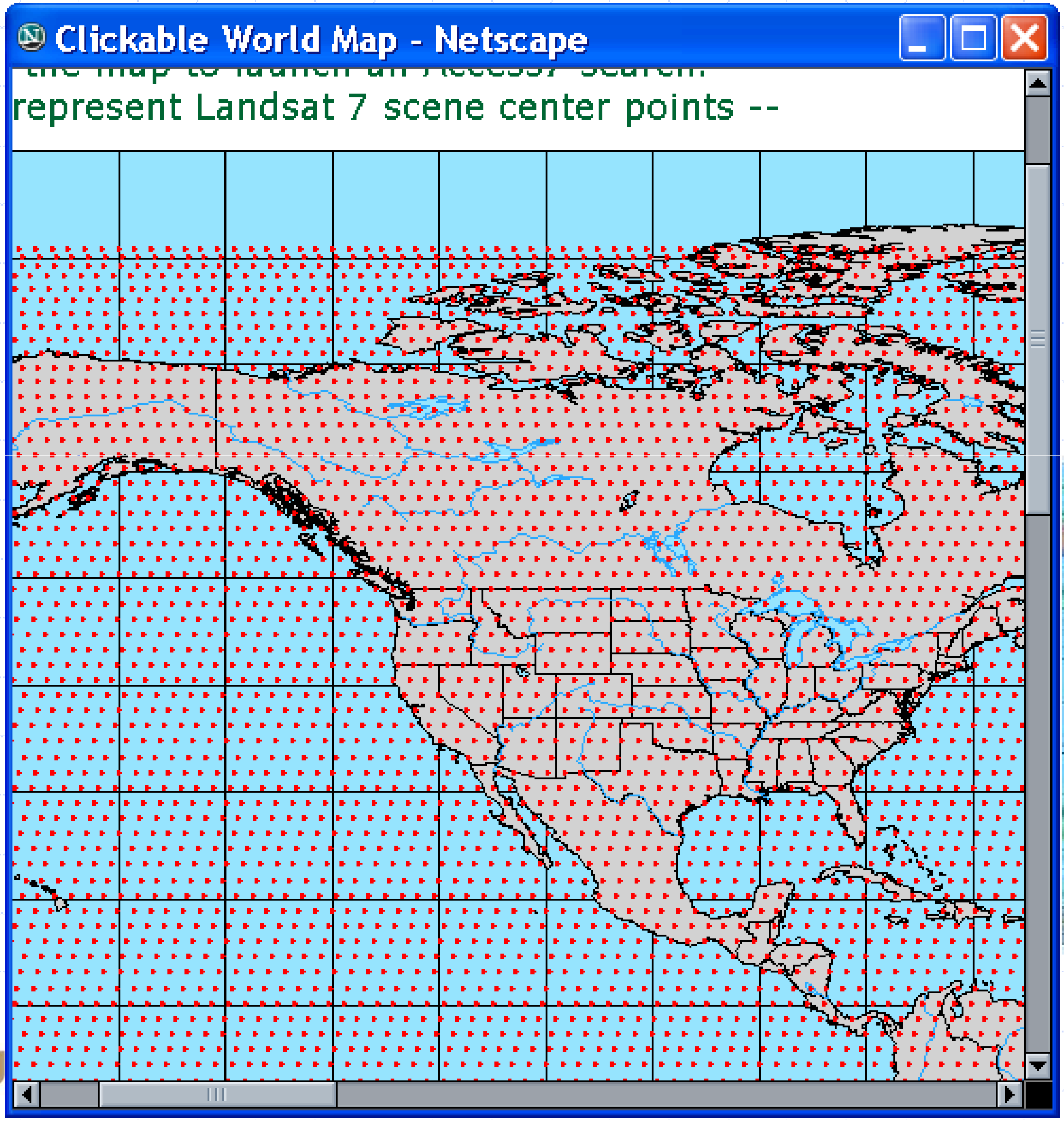
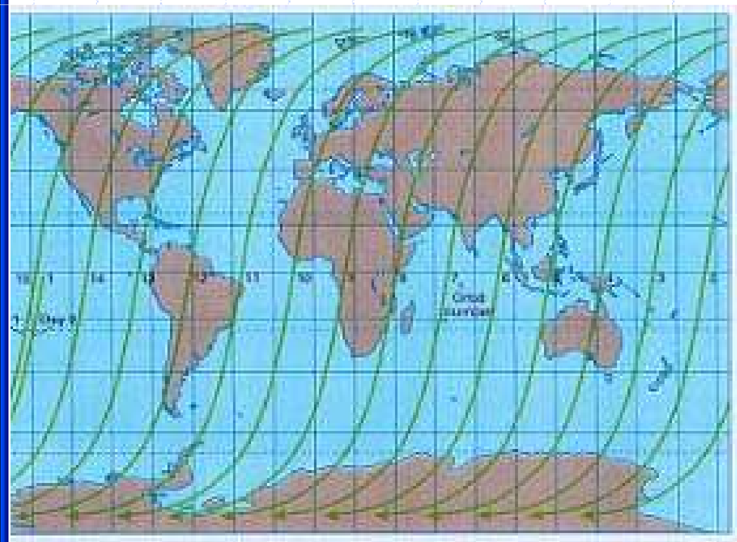
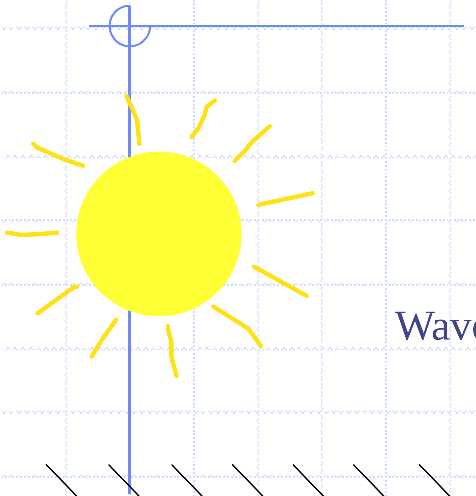
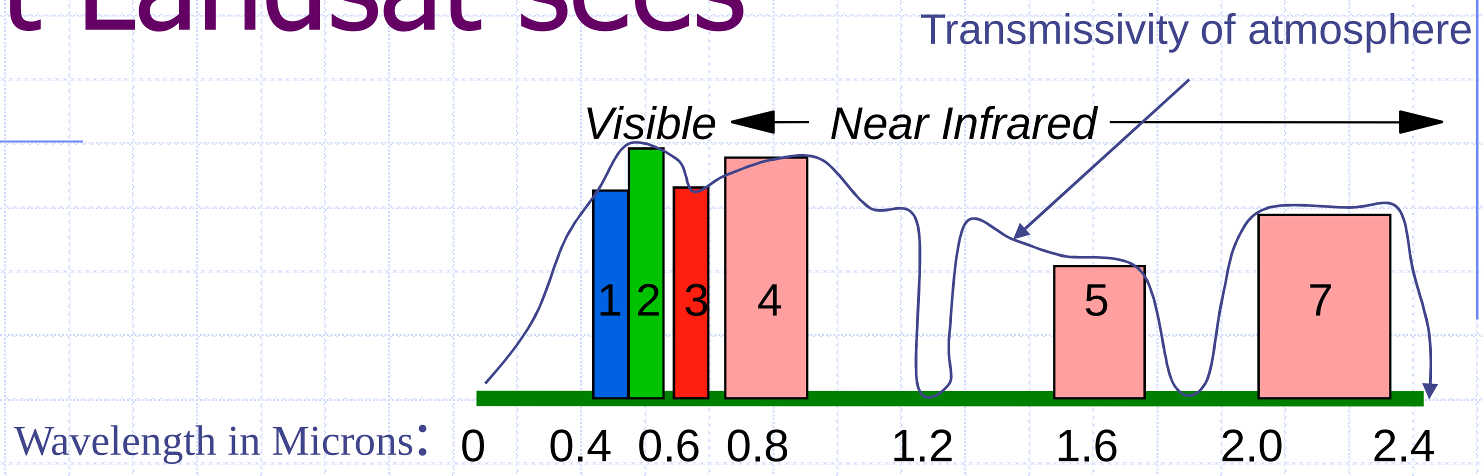
Landsat – Polar Orbiting



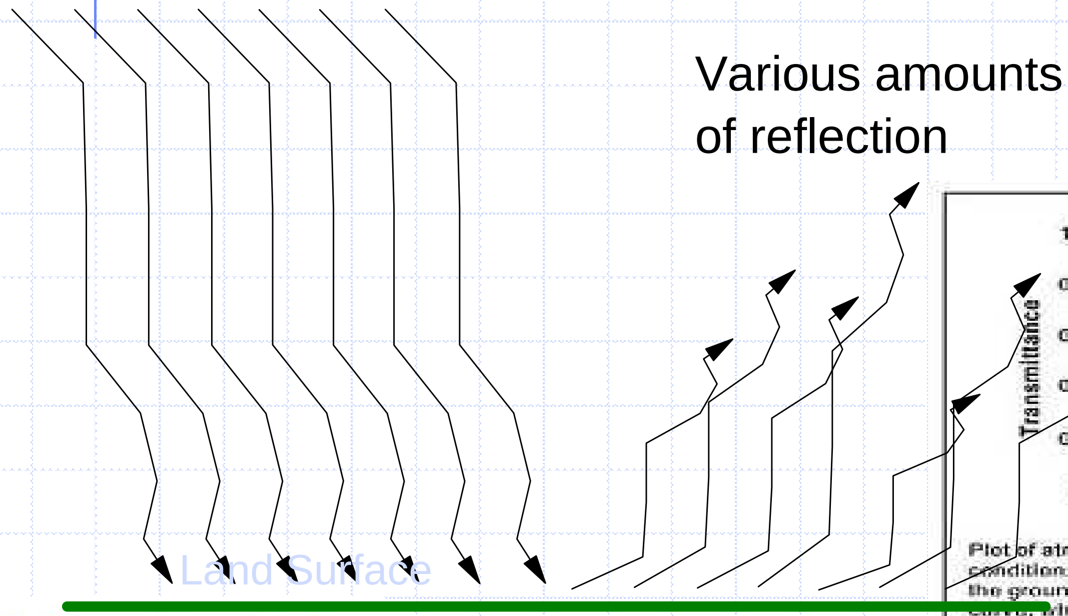


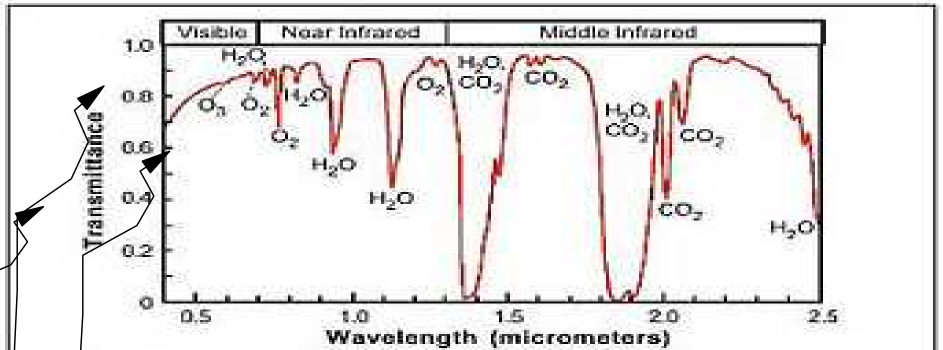
What Landsat sees





(Band 6 is the surface temperature band (not shown))

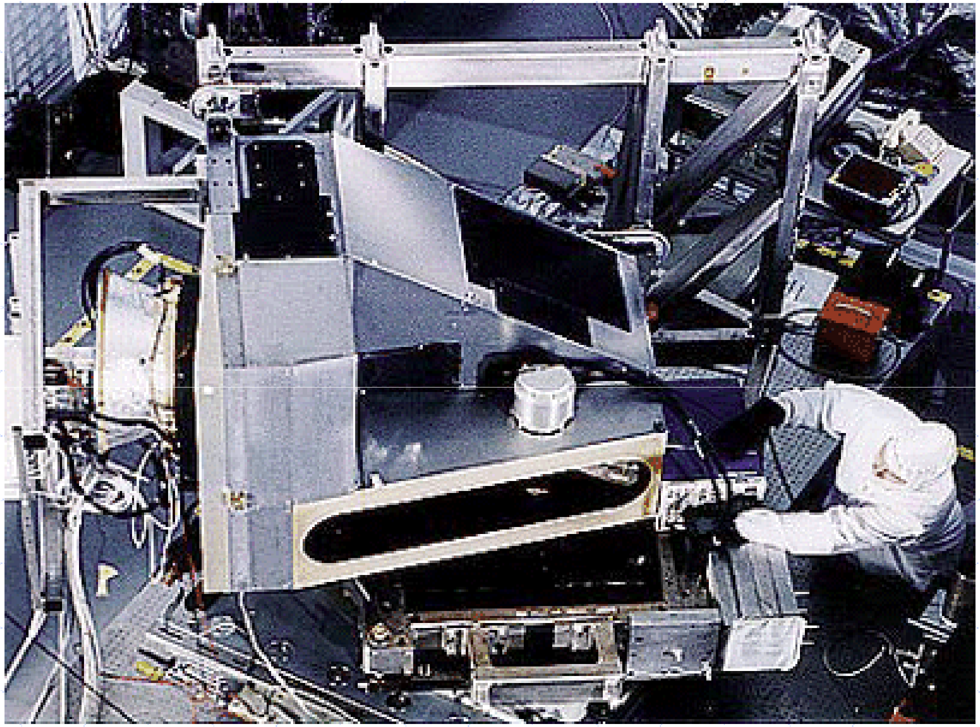


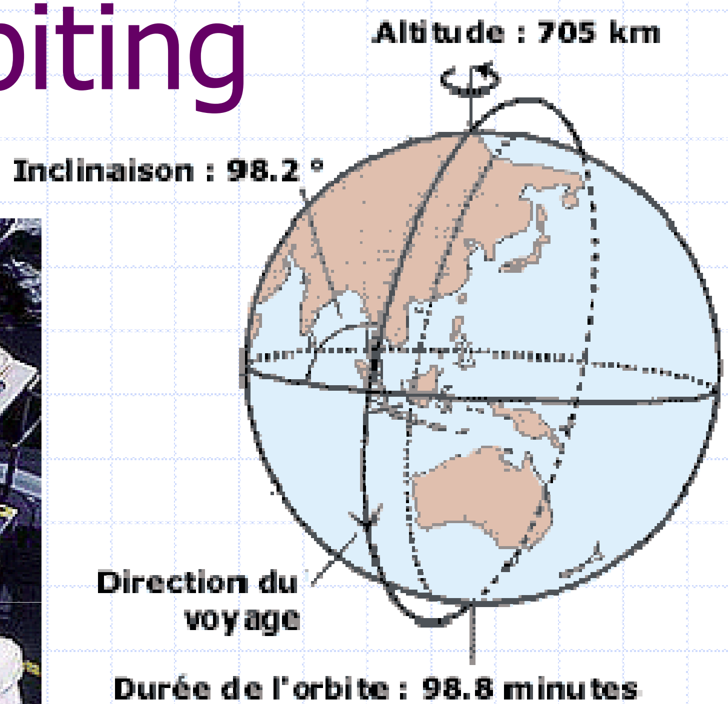


Plot of atmospheric transmittance versus wavelength for typical atmospheric conditions. Transmittance is the proportion of the incident solar energy that reaches the ground surface. Absorption by the labeled gases causes pronounced lows in the curve, while scattering is responsible for the smooth decrease in transmittance with decreasing wavelength in the near infrared through visible light wavelength range.

MODIS – Polar Orbiting

705 km, 10:30 a.m. (Terra) and 1:30 p.m. (Aqua)



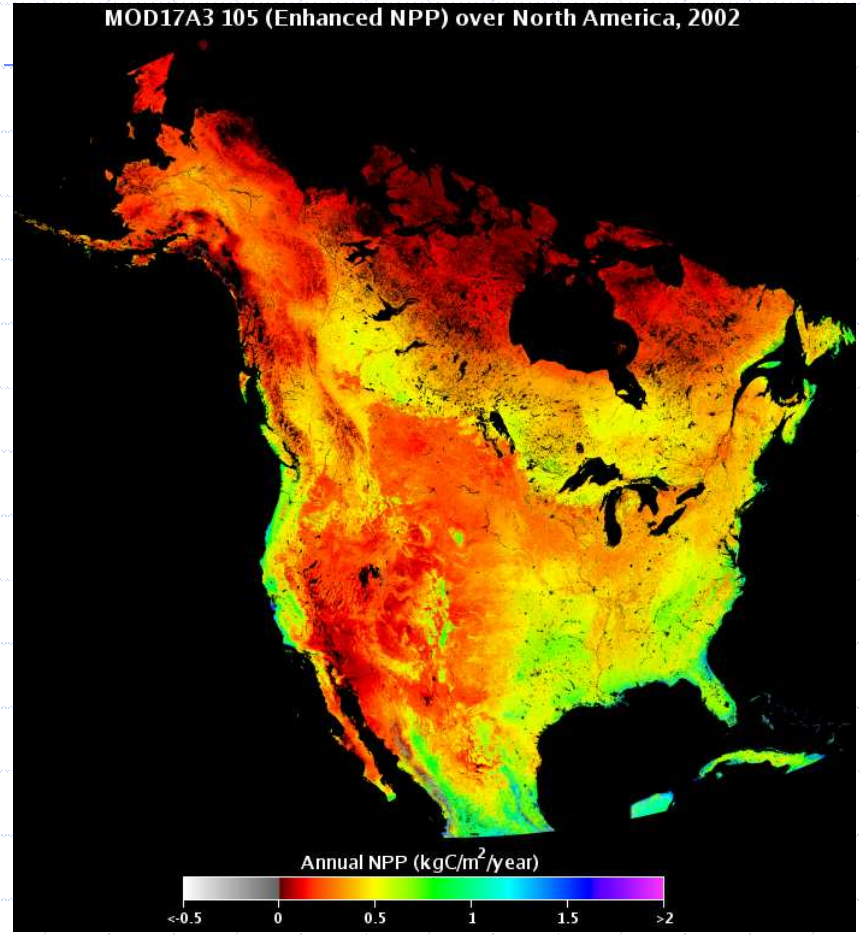


36 bands

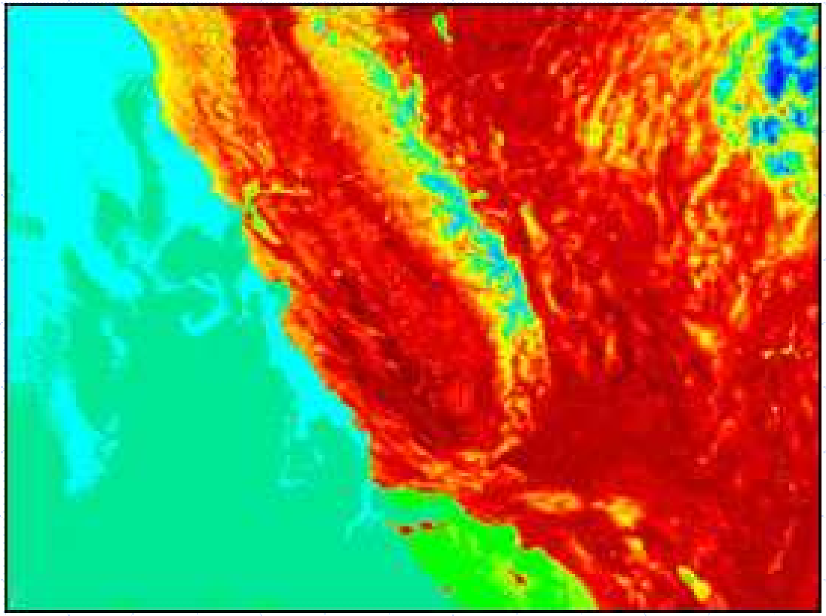
-- most at 1 km resolution

A new image ***each day*** *for a region*

MODIS – Polar Orbiting



BIOMASS Net Primary Productivity for North America



Surface Temperature, Southern California, Record Weather, May 2, 2004

Many "products" at 1 km (0.62 mile) resolution

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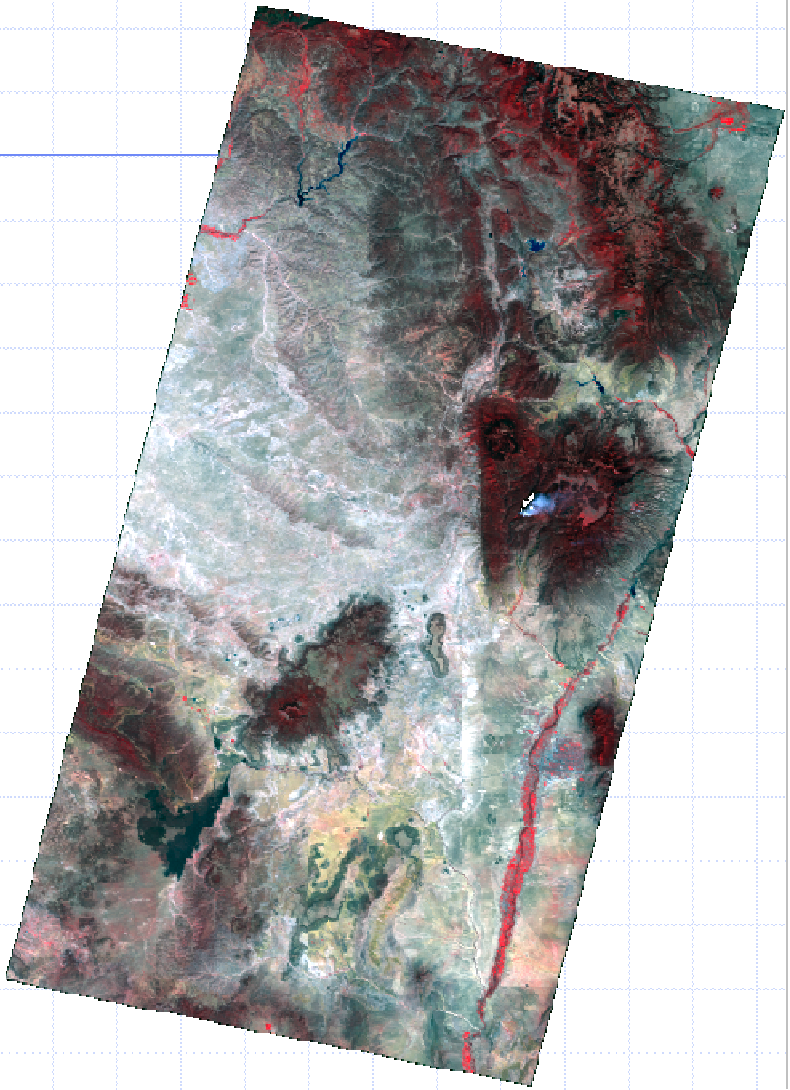
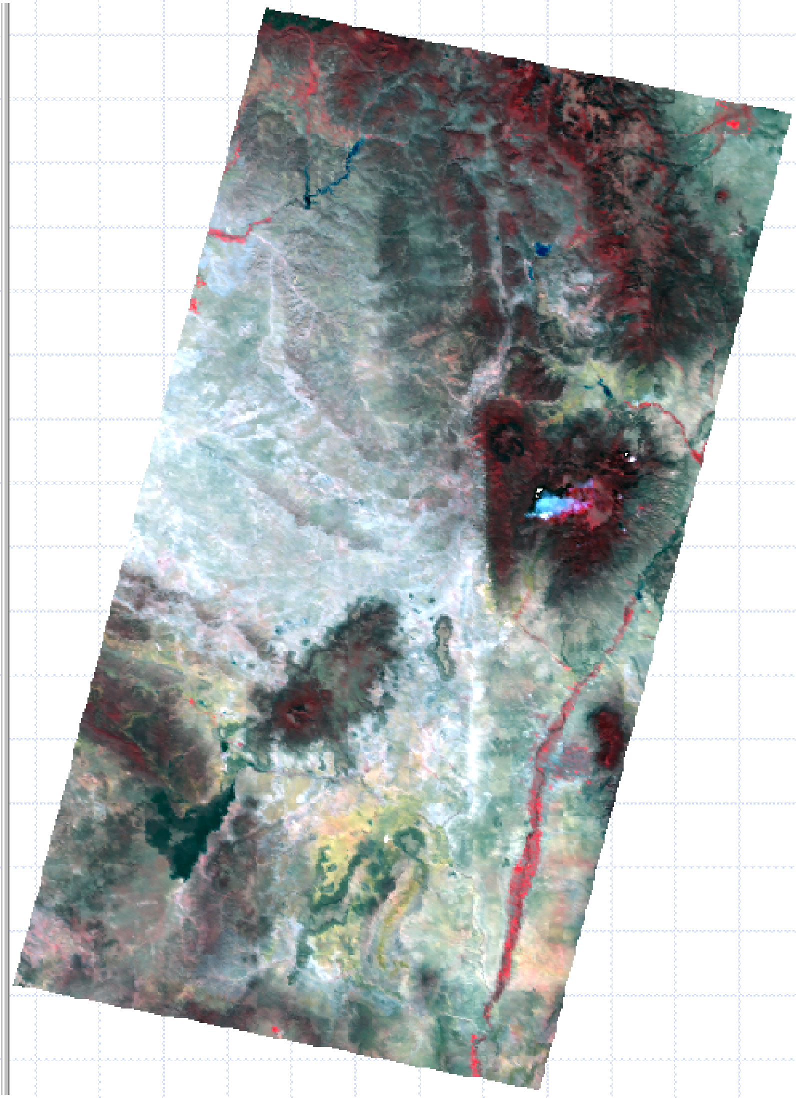
Landsat vs MODIS

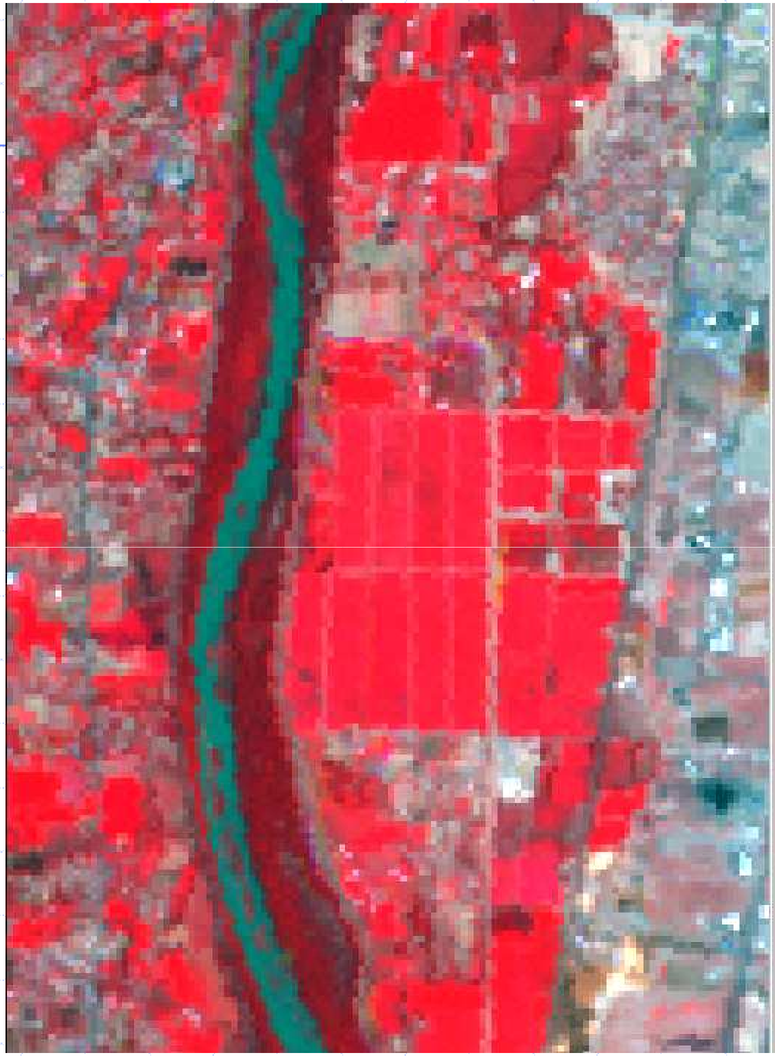


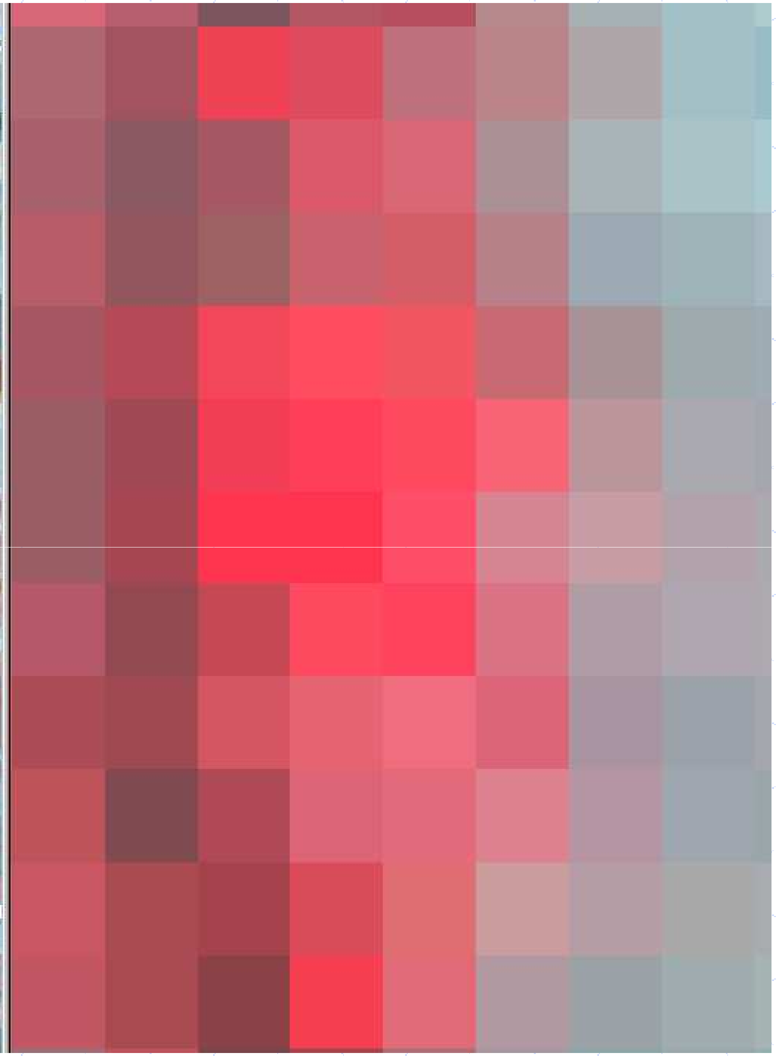
Landsat False Color
(path 34, row 36 (MRG))
8/26/2002 10:33am



MODIS False Color
(equiv path 34/36 area)
8/26/2002 11:02am

Landsat vs MODIS





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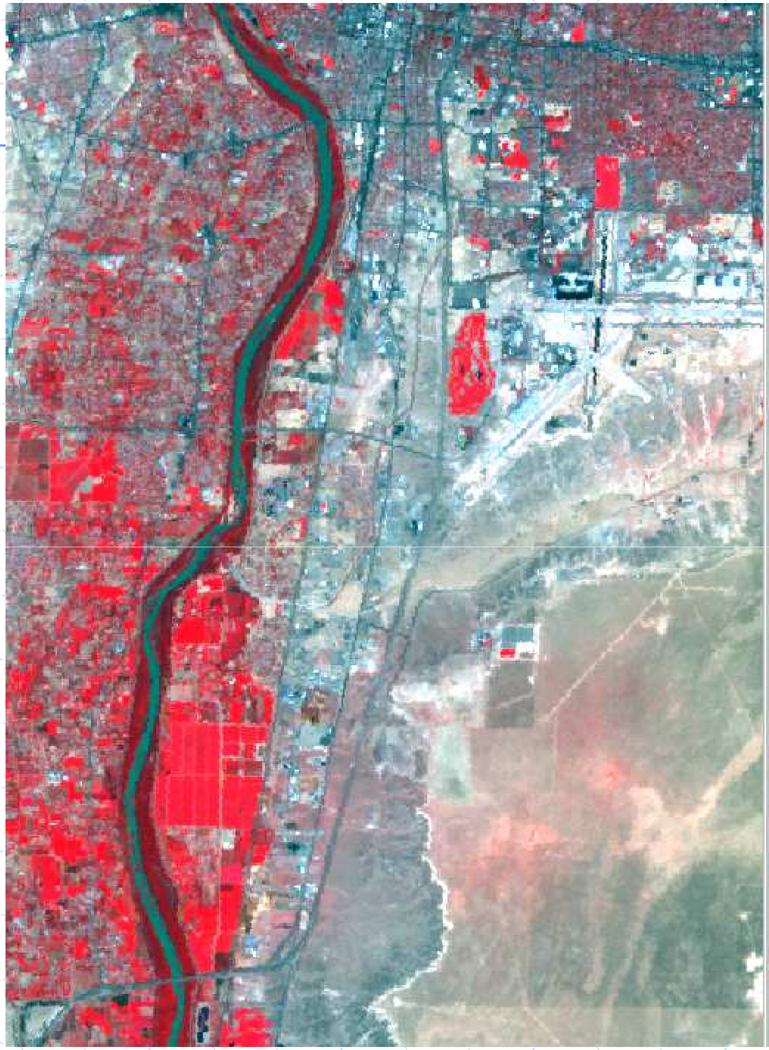
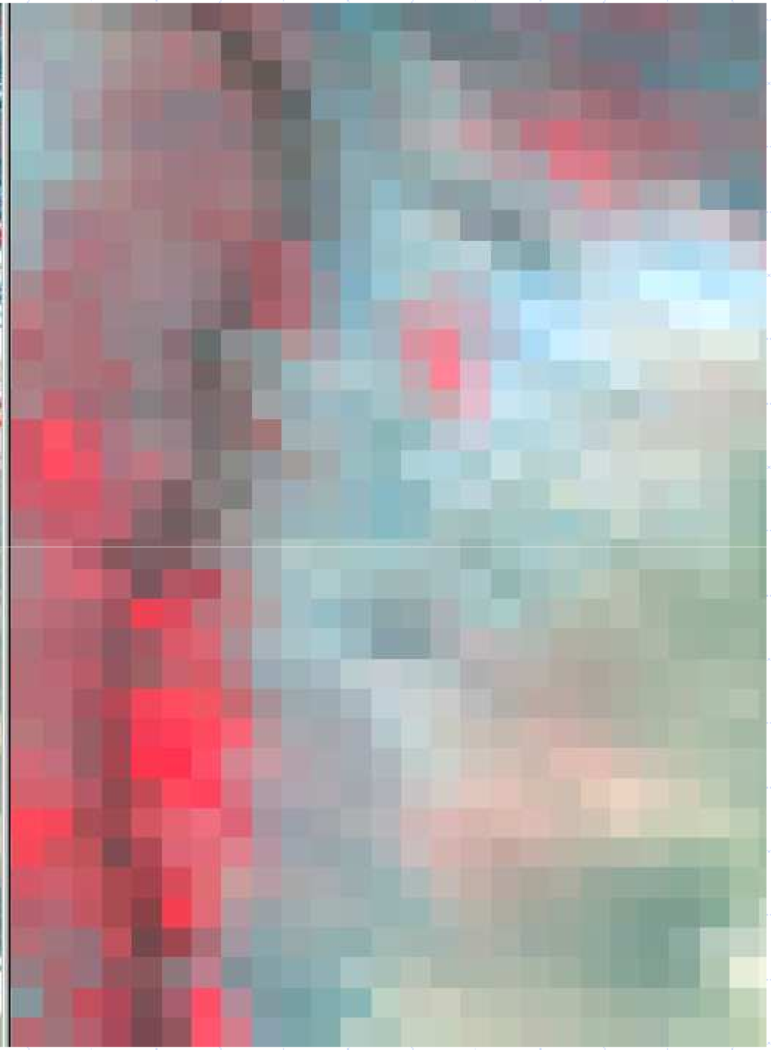
Landsat vs MODIS





Landsat False Color (MRG)
8/26/2002 10:33am

MODIS False Color (MRG)
8/26/2002 11:02am

Satellite Compatibility

- METRIC^{tm} needs both short wave and thermal bands

- METRIC^{tm} can use images from:
  - NASA-Landsat (30 m and 60 to 120 m resolution each 8 or 16 days) since 1982
  - NOAA-AVHRR *(advanced very high resolution radiometer)* (1 km, daily) - since 1980's
  - NASA-MODIS *(moderate resolution imaging spectroradiometer)* (500 m to 1000 m daily) - since 1999
  - NASA-ASTER *(Advanced Spaceborne Thermal Emission and Reflection Radiometer)* (15 m, 8 days) - since 1999

Why Use METRIC^{tm} or SEBAL?

- ET via Satellite using METRIC^{tm} or SEBAL can provide dependable (i.e. accurate) information
- ET can be determined remotely
- ET can be determined over large spatial scales
- ET can be aggregated over space and time
- In METRIC, the ET surface can be 'tied down' using reference ET (accounting for advection)

Accuracy of ET by Satellite Energy Balance

What can we expect?

- Satellite is 705 km above the earth
- Besides energy "seen" by satellite, ET is impacted by aerodynamics ***invisible*** to the satellite
- Need to key aerodynamic characterizations off image
- Design of SEBAL and METRIC make process relatively ***insensitive*** to the parameterization of aerodynamics
- "***Magic***" of the temperature difference (dT) vs. surface temperature function of SEBAL (Bastiaanssen 1995, 1998) provides internal and relatively automatic calibration

How METRIC[tm] Works

METRIC[tm] keys off:

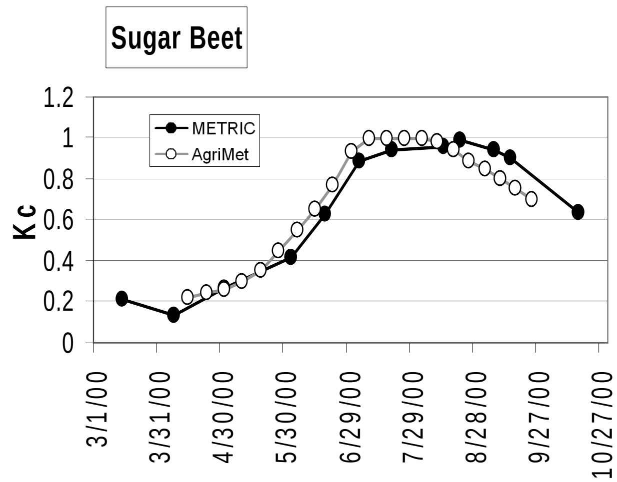
- reflectance of light energy
- vegetation indices
- surface temperature
- relative variation in surface temperature
- general wind speed *(from ground station)*

Accuracy of ET by Satellite Energy Balance

What can we expect?

- **METRIC** is an "**engineer's tool**"
- Focus is on a '**small**' region of interest **(100 miles x 100 miles)** (i.e, not the world, not 17 western states)
- **METRIC combines** the strengths of energy balance from satellite and accuracy of ground-based reference ET calculation:
  - **satellite-based energy balance** provides the spatial information and distribution for a large area (and does most of the "**heavy lifting**")
  - **reference ET calculation** "**anchors**" the energy balance surface and provides "reality" to the product.

What is the Alternative to Satellite Energy Balance?



- **ET = Crop Coefficient x Reference ET (i.e., K_c x ET_r)**

  -- note that K_c is synonymous with **ET_rF** (fraction of **ET_r**)

- **K_c curve** is a continuous ratio of ET to ET_r over the life of a crop.
  - General curves are available from only five or six experimental sites.
  - Accuracy of the K_c estimate for any specific field is probably **+/- 10%** at best

- The ASCE-EWRI standardized **Reference ET** method, if used with high quality weather data, is **+/- 10%** for a given location

- The **K_c ET_r product** is probably **+/- 15%** for any specific field and perhaps **+/- 10%** over an area ***(if done well).***

Accuracy of ET by Satellite Energy Balance

What can we expect?

- Because **METRIC** uses ET_r to tie to and by which to integrate ET over time, ET from METRIC incorporates any errors and bias of the ET_r calculation
- Extrapolation over an area is similar to K_c ET_r approach
  - Use **ET_r** surface to represent climatic demand
  - **Whereas**: Satellite energy balance incorporates effects of vegetation density, water availability (via T_s) etc. in the calculation of **specific ET by field** (K_c curve usually does not)
- **Accuracy** of ET by **METRIC** is probably
  - +/- 10 to 20% for a specific field on a specific day
  - +/- 10 to 15% for many fields on a specific day
  - +/- 10 to 15% for a specific field over a season

(if done well)

Why we selected the SEBAL Model and evolved the METRIC^{tm} Model

CIMEC: The <u>energy balance</u> and ET predictions are **internally calibrated** to <u>*two known ET rates*</u>:

An internalized calibration function for “H” is constructed within SEBAL (and METRIC)

<u>*In Classical **SEBAL**:*</u>

1. ~zero ET → bare, dry agricultural soil

2. ET ~ R_n – G – (H~0) →“wetter” vegetated pixels (or $H_2$0)

<u>*In **METRIC**:*</u>

2. alfalfa reference ET →“wetter” cropped pixels

Much less need to apply extensive atmospheric corrections or depend upon absolute temperature gradients (because of the internal calibration)

Why we selected the SEBAL Model and evolved the METRIC^{tm} Model

METRIC and SEBAL are "***crop classification free***"

- No need to perform an extensive, expensive crop classification
  (may be required to apply ET_fF vs. vegetation index relations)
- A crop classification might cost more than applying the full energy balance of METRIC or SEBAL

METRIC^{tm}: **M**apping **E**vapo**t**ranspiration with High **R**esolution and **I**nternalized **C**alibration

METRIC is tied down to *everything* we *know* about ET that is *straightforward* and *good*

(i.e., ET_r)

ET_r contains information on:

- Direct impact of wind speed on ET process
  - at image time
  - during the day *(for extrapolation)*
- Impact of vapor pressure deficit and other advective factors
  - at image time
  - over the course of the day *(for extrapolation)*
- Impact of afternoon clouding on daily ET *(for extrapolation)*

Plus, the approach is congruent with the alternative (K_c ET_r)

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SEBAL and METRIC^{tm}

are complementary:

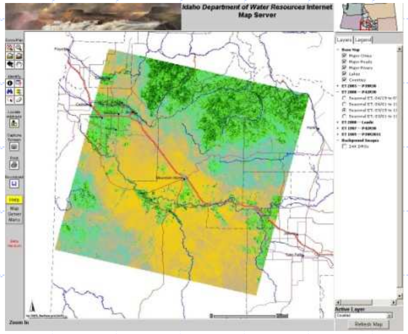
use SEBAL when high quality hourly electronic weather data are not available.

use METRIC^{tm} otherwise for improved accuracy under advective conditions

Image Processing

- ERDAS *Imagine* used to process *Landsat* images
  - METRIC^{tm} equations programmed and edited in ***Model Maker*** function
  - 8 functions / steps run per image

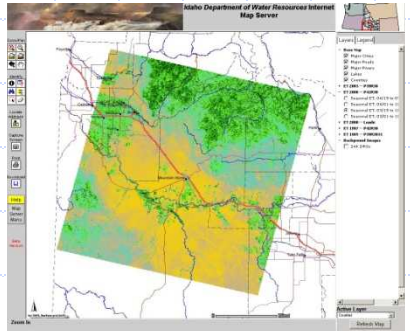
METRIC^{tm} Level One



- ***Robust*** set of equations and procedures
- For <u>general application</u>
- ***<u>Applications manual</u>*** includes instructions and recommendations
- Includes algorithms for application in mountainous terrain (Appendix 12)
- Accuracy requires
  - ***Intelligence***
  - ***Insight***
  - ***Iterative Review***

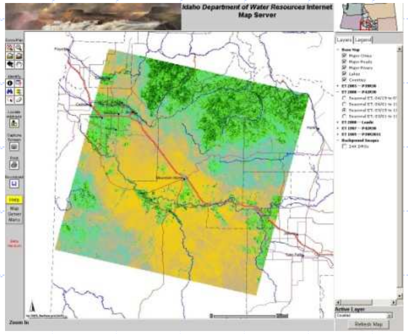
METRIC^{tm} is an ***<u>Engineering Tool</u>***

METRIC^{tm} Level Two



- Equations and procedures (potentially) **modified** and **customized** *<u>for each application</u>* area:
  - Multiple dT functions (calibrations) for complex subareas
  - Limits on dT function
  - Customized albedo and three source T_s estimation
  - Modification of soil heat flux computation
  - Refined selection of hot pixel
  - Excess aerodynamic resistance for sparse vegetation
  - Available energy for water bodies

METRIC^{tm} Level Two

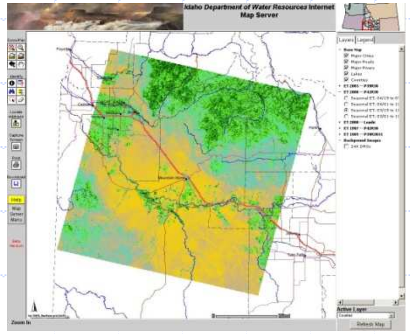


- Customized modifications rely as much on operator behavior, care, understanding and judgment as in modification of equations

- Level Two requires even more
  - ***Experience***
  - ***Understanding (of physics and processes)***
  - ***Insight***
  - ***Iterative Review***

- Level two is not for general release

METRIC[tm] Level One Operator requirements



- ***Background in:***
  - ***Hydrologic science or engineering*** *(to know behavior of soil, vegetation and water systems)*
  - ***Environmental physics***
    - *Radiation*
    - *Aerodynamics*
    - *Heat transfer*
- ***Familiarity with***
  - ***Vegetation systems*** *(to know what one is looking at and growth and canopy characteristics)*
  - ***Specific human activities*** *(agriculture, irrigation, etc.)*
  - ***Remote Sensing*** *Science and Applications*
  - ***Image Processing***

Next Section: More Background